The Testing of the 1:8 Scale Model Of the R-Class in Level Ice

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Un sommaire en français de ce rapport est inclus avant la Table des matières.

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17. Abstract

A comprehensive series of level ice resistance tests was performed on a 1:8 scale model of the R-Class icebreaker. Ice tests with three velocities, three ice thicknesses and two ice strengths were performed. Additional ice tests were performed with the ice sheet pre-sawn to the approximate size of broken floes. These results were compared with both full scale data and 1:20 model scale data to examine the influence of scale in model ice testing.

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17. Résumé

Une série d'essais en modèle réduit à l'échelle 1/8 ont été effectuées, afin d'évaluer la résistance d'un couvert de glace uniforme sur le brise-glace du type "R-Class". Ces essais ont été faits avec trois épaisseurs de glace, trois vitesses de croisière, et deux valeurs de contrainte en flexion de la glace. Des essais additionnels ont été effectués avec un couvert de glace pré-rupturé. Les résultats ont été comparés aux résultats obtenus en nature, et aussi aux résultats des essais en modèle réduit à 1/20 d'échelle dans le but d'évaluer l'effet de l'échelle sur les résultats en modèle réduit.

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The assistance given by the Memorial University work term students is also gratefully appreciated.

SUMMARY

This report describes the experimental procedures, the results and the analysis of level ice resistance tests performed on a 1:8 scale model of the Canadian R-Class icebreaker.

The data from these 1:8 scale tests is compared with limited full scale data. While the agreement at times is excellent, there is insufficient full scale data available in snow-free ice to perform a detailed analysis of scale effects.

The 1:8 data is also compared with previous 1:20 model data. Again, the agreement at times is very satisfactory. However, model test procedures differ between test facilities and even between test personnel.

This report, in conjunction with an identical test program being performed at the Institute of Marine Dynamics on 1:20 and 1:40 scale models of the R-Class, should provide sufficient data to determine the effect that model scale has on model ice testing. Additional full scale testing of this vessel in high quality snow-free ice is however still desirable for continued investigation of model/full scale correlation.

RESUME

Ce rapport décrit les procédures expérimentales, les résultats et analyses de la résistance dans un couvert de glace uniforme du brise-glace de classe "R" (GCC "Radisson") à une échelle de 1/8.

Les données obtenues au cours des essais ont été comparées à celles obtenues en nature. Bien que la corrélation entre les deux types d'essais soit très satisfaisante, il n'y a pas suffisamment de données en nature sur de la glace libre de neige pour permettre une analyse détaillée d'effets d'échelle.

Les données des essais à l'échelle 1/8 ont aussi été comparées à des essais précédents à l'échelle 1/20. La corrélation trouvée était, encore une fois, très satisfaisante. Toutefois, les procédures d'essais en laboratoire peuvent varier suivant l'équipement des laboratoires et même suivant le personnel effectuant les essais.

Les résultats de ce rapport, conjointement avec les résultats d'essais identiques faits à l'Institut de Dynamique Marine mais aux échelles 1/20 et 1/40 du brise-glace classe "R", pourront fournir des données suffisantes pour déterminer l'effet d'échelle sur les résultats obtenus en laboratoire. Cependant, des essais additionnels en nature du brise-glace de classe "R", sur glace uniforme et sans couverture de neige, semblent nécessaires pour compléter l'étude de la corrélation entre les essais sur modèles et les essais en nature.

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NOMENCLATURE

B	-	Breadth
B_{WL}	-	Breadth at the Waterline
C_b	-	Block Coefficient
C_{bf}	-	Forward Block Coefficient
C_m	-	Midship Coefficient
$C_0, C1, \ldots$	-	Coefficients
C_p	-	Prismatic Coefficient
C_w	-	Waterplane Coefficient
C_{wf}	-	Forward Waterplane Coefficient
F	-	Force
$fn(\ldots)$	-	Function of ...
H	-	Full Scale Velocity
h	-	Model Ice Thickness
KB	-	Distance from Keel to Centre of Buoyancy
KG	-	Distance from Keel to Centre of Gravity
KM	-	Distance from Keel to Metacentre
L	-	Length
L_{BP}	-	Ship Length between Perpendiculars
LOA	-	Overall Ship Length
L_{WL}	-	Ship Length at Waterline
$n_0, n_1, \ldots$	-	Power Coefficients
P	-	Force Required to Break a Cantilever Beam
R_{ow}	-	Open Water Resistance
R_I	-	Ice Resistance
R_T	-	Total Resistance

NOMENCLATURE CONTINUED

T	-	Propeller Shaft Thrust
t	-	Thrust Deduction Factor
T_{fwd}	-	Forward Draft
T_{mean}	-	Mean Draft
V	-	Volume
v	-	Model Velocity
α	-	Waterline Angle
β	-	Flare Angle (at Waterline)
β_5	-	Midship Flare Angle
σ_f	-	Flexural Strength
ρ_i	-	Mass Density of Ice
ρ_w	-	Mass Density of Water
γ_o	-	Stem Angle
μ	-	Hull Friction Coefficient
λ	-	Scale Factor
Δ	-	Displaced Mass

1. INTRODUCTION

The testing of model ships and structures in ice has always been subject to the question of how the choice of scale affects the results. In the past, the only method of answering this question was to compare the model results with full scale data. This was due to the limited range of scales able to be tested in smaller ice basins. However, by addressing the scale effect question by comparison of model results with full scale data, more questions arose than were answered.

Most full scale data sets embody numerous assumptions. Firstly, there are very few full scale tests where the hull/ice friction factor is completely known. For those tests where the hull/ice friction factor was measured, it was measured at or above the waterline. Indeed the technique of measuring hull/ice varies and may not be directly comparable with model procedures.

Secondly, the primary factors which affect ice resistance are the ice properties. Most full scale ship trials measure the ice strength indirectly, if at all, and measure the ice thickness only periodically. Therefore, the errors in predicting icebreaking performance due to errors in the ice properties, can be significant.

Finally, full scale ship tests measure the propeller thrust required to propel the vessel through the ice, whereas in the model basin, the towed resistance is usually measured. These two parameters can be compared if the propeller thrust deduction factor is known. However, the error in measuring this factor in model scale is of the order of 20 to 30%. Therefore, attempting to determine the model scale effect by comparison with full scale data is fraught with factors that detract from accurate comparison.

With the new large ice tank at the Institute for Marine Dynamics (IMD) operational, another opportunity to investigate the scale effect is available. The IMD ice tank is the largest in the world; 93 m long, 12 m wide and 3 m deep. Its ice growth area is 78 m long, with 13 meters for model preparation. These dimensions place this facility in a class of its own. The prepared ice surface at IMD is 56% larger than the ice at the Hamburg Ship Model Basin (HSVA) and 140% larger than at the Wartsila Arctic Research Centre (WARC) facility, permitting larger models to be tested at IMD. By using IMD, it is now possible to extend the usable scale range down to 1:8. With a five fold variation in scale factor, it should be possible to investigate scale effects

This report describes the experimental procedures, the results and the analysis of the results of level ice resistance tests performed on a 1:8 scale model of the R-Class icebreaker. This project, in conjunction with identical test programs being performed on the 1:20 and 1:40 scale models, will provide sufficient data regarding the scale effects of model ice testing.

2. MODEL DESCRIPTION

The model tested in this program was the 1:8 scale model of the Canadian R-Class icebreaker as shown in Figure 2.1. The model was constructed of foam and wood with a fibreglass shell. The model was of the bare hull form, without any appendages.

The condition tested was the ITTC recommended test draft for the R-Class. This condition matched a limited number of full scale data points obtained by NRC for the CCGS SIR JOHN FRANKLIN. Table 2.1 lists the model particulars for this condition.

Before testing, the ballast was distributed longitudinally to give a radius of gyration of approximately 1/4 the ship's length and distributed vertically to give an insitu roll period of 4.1 seconds. The metacentric height was also measured.

FIGURE 2.1

1:8 MODEL OF THE R-CLASS

TABLE 2.1

Model Hull Data Sheet

Model Number	Vessel Name	Scale
M 389	R-CLASS	1:8

Dimensional Parameters

L_{OA} = 12.290 m

L_{WL} = 11.625 m

L_{BP} = 10.992 m

B_{WL} = 2.420 m

T_{fwd} = 0.846 m

T_{aft} = 0.902 m

T_{mean} = 0.876 m

Δ = 15,245 kg

KG = 0.969 m

KM = 1.096 m

KB = 0.485 m

Roll Period = 4.1 sec.

Nondimensional Parameters

C_b = .611

C_{bf} = .592

C_p = .665

C_w = .799

C_{wf} = .772

C_m = .919

γ_o = 18°

β_5 = 5.5°

L/B = 4.804

B/T = 2.763

Hull Friction Coefficients

$\mu_0 = 1 + \mu_1(0) = 1.582$

$\eta_2 = 1 / \mu_2(0) = 2.717$

Hull Friction Factor

μ = .135 @ σ_f = 60 KPa

.112 @ σ_f = 100 KPa

Geometric-friction Coefficients

μ	μ_1	μ_2
0.000	.582	.343
0.100	.780	.479
0.200	.978	.628
0.300	1.176	.791
0.400	1.373	.971
0.500	1.571	1.170

Forebody Waterplane Angles

Station	10 (FP)	9 1/2	9	8 1/2	8	7 1/2	7	6 1/2	6	5 1/2	5
$\alpha°$	29	28	23	14.5	8.5	5.5	3.5	2.5	1	0	0
$\beta°$	50	43	33	22	12.5	10	7	6.5	5.5	5.5	5.5

3. MEASUREMENT TECHNIQUE

3.1 Model Resistance Tests

Prior to the model being placed in the towing tank, the model's surface was set to the desired friction factor. Due to practical limitations of measuring the hull/ice friction factor on a model of this size, a friction plank was prepared at the same time as the model. Surface roughness measurements were made randomly on both the hull and the friction plank to confirm that they were both approximately equal.

The model was placed in the ice basin and ballasted to the conditions listed in Section 2. With the model ballasted at the correct waterline, the roll period and GM (the distance between the centre of gravity and the metacentre) were measured and adjusted insitu.

The model was then attached to the towing post at its centre of gravity, and the data acquisition system configured as shown in Figure 3.1. The model motion was measured with three LVDT's (Linear Variable Differential Transformer). One LVDT was mounted on the heavestaff to port, another to starboard and the third towards the bow. From trigonometry, the roll, pitch and heave can be calculated from these LVDT's. Figure 3.2 shows the towing post, the towing gimbal and the three LVDT's. Figure 3.3 shows the positions of the LVDT's relative to the towing post.

The model's resistance was measured with a 5000 N strain gauged load cell rigidly mounted to the model as shown in Figure 3.4. The load was transferred between the model and the towing carriage by the towing post, which was rigidly fixed to the carriage. A linear bearing, mounted within the towing post gimbal, gave the model freedom to heave. The gimbal added freedom to roll and pitch. The entire gimbal was fixed to a wishbone, which was attached to the model by three linear bearings. These bearings rigidly fixed the wishbone to the model in all directions but the resistance direction.

Across the aft end of the wishbone was a load bar which simply butted up against the load cell. Since the load bar was not rigidly attached to the load cell, two coil springs were located on the wishbone to apply a pretensioning load.

To prevent damaging the load cell, stops were placed on the wishbone to constrain its axial displacement. These stops were set at approximately 6800 N. There was approximately 2600 N preload applied to the pretensioning springs. Therefore the resistance range was set between +4200 N and -2600 N.

As a precaution, the resistance measurement was measured twice, through independent wiring, conditioners, amplifiers and computer channels.

A second heavestaff was placed 3.088 m aft of the towing post to restrain the model in yaw as shown in Figure 3.5. The yaw restraint post was located between two longitudinal rollers which gave freedom to roll, pitch, heave and surge. Two load cells were mounted in the transverse direction to record lateral force.

Figure 3.1 IMD's DATA ACQUISITION SYSTEM

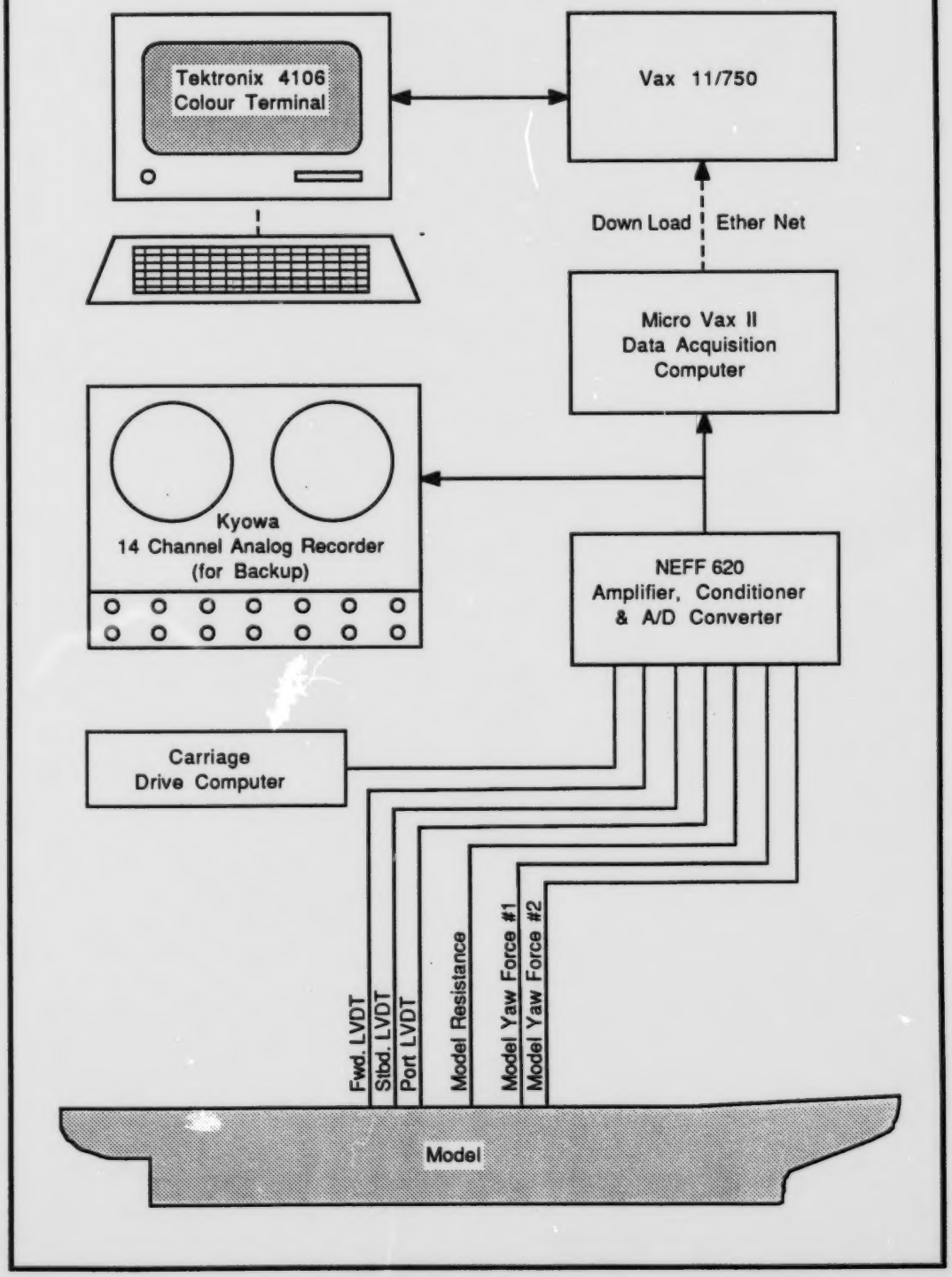


FIGURE 3.2

IMD's TOWING POST

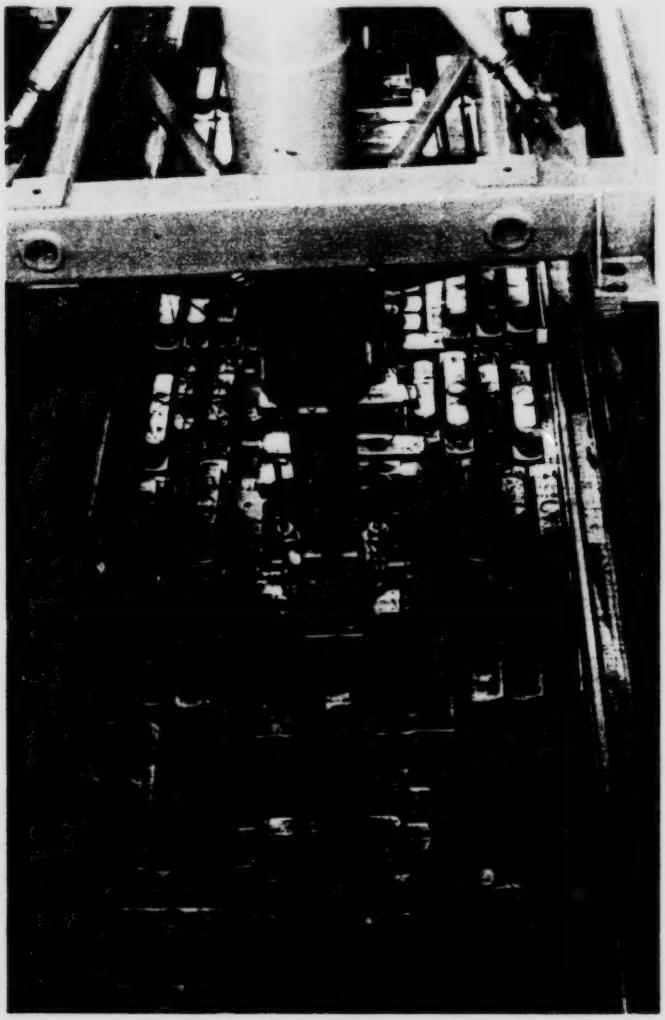


Figure 3.3 HEAVESTAFF / LVDT ARRANGEMENT

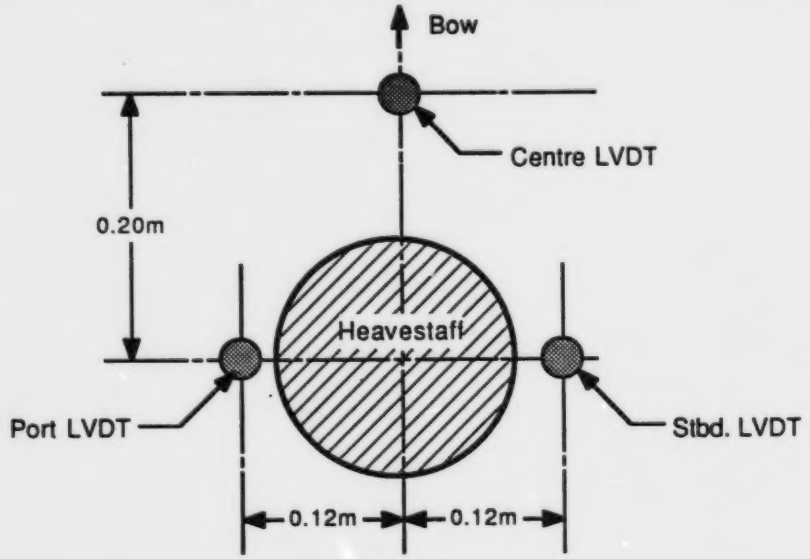


FIGURE 3.4

IMD's TOWING GIMBAL

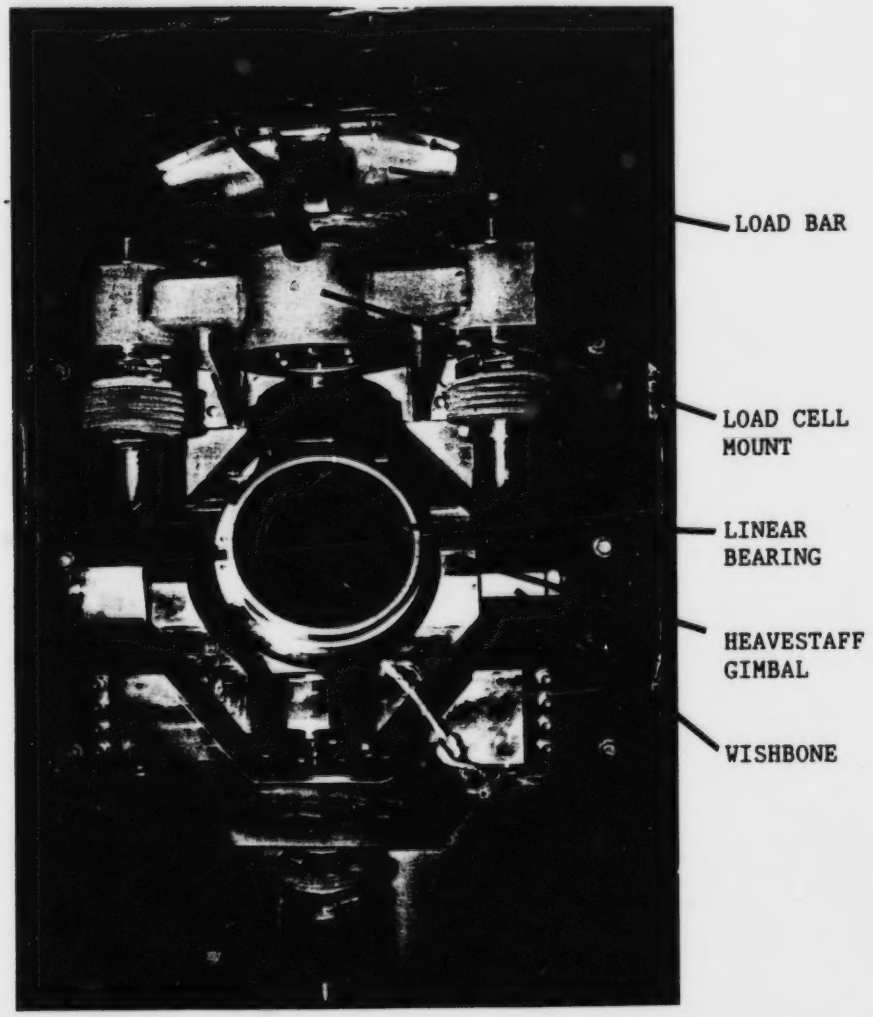
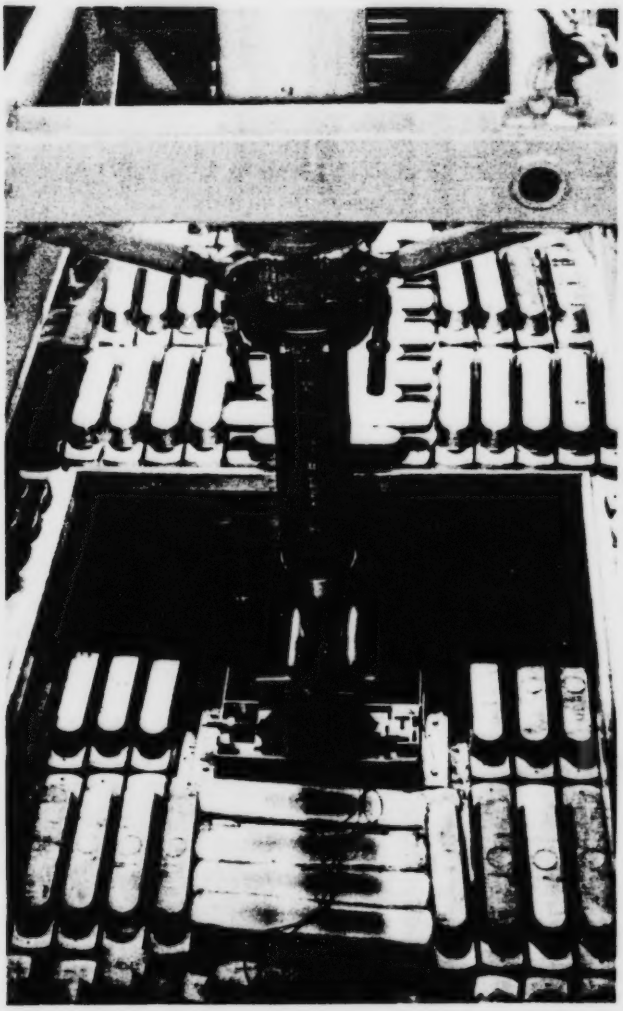


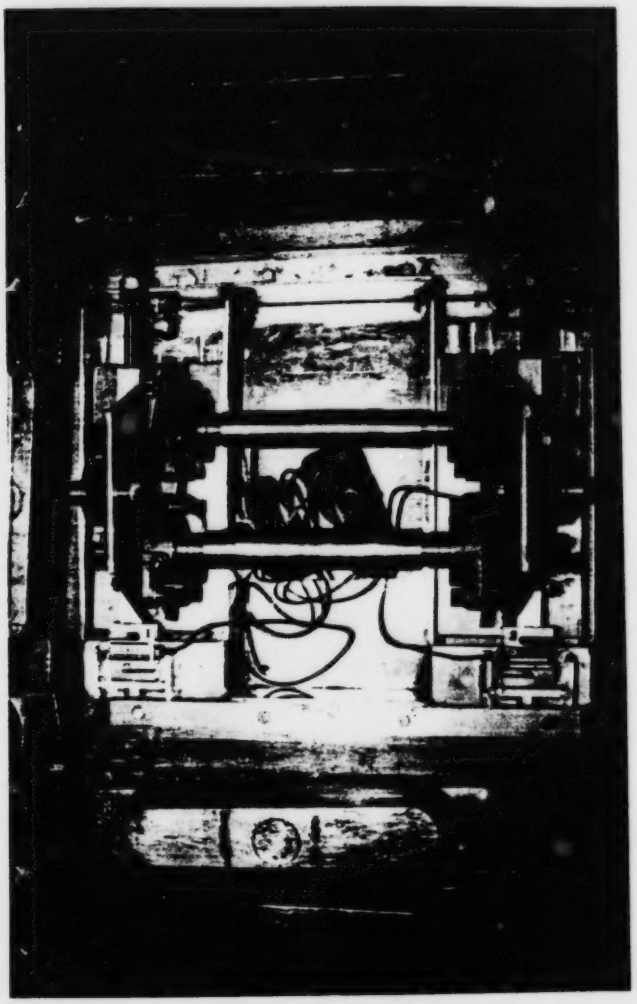
FIGURE 3.5

YAW RESTRAINT

a) TOW POST



b) GIMBAL



The carriage velocity was tapped off the carriage drive system's control computer.

The calibrations were all done insitu through the entire data acquisition system. The calibrations for the three LVDT's were done with a set of precision blocks. These blocks were used to displace the core of the LVDT while the voltage signal was being sampled by the computer.

The model resistance was calibrated with an auxiliary load cell. To begin with, the auxiliary load cell was calibrated with dead weights and the aid of a 3 ton crane. The auxiliary load cell was then connected between the model and the end wall of the basin with a wire rope. A come-a-long was then used to tension the wire rope, which in turn applied a force to the model. The output of the auxiliary load cell was manually measured with a precision voltmeter while the resistance signal was being sampled by the computer.

The yaw force was calibrated in a similar manner to the resistance. The auxiliary load cell was connected between the model and the side wall of the basin with a wire rope. The come-a-long was again used to tension the rope.

With all transducers calibrated, the testing could begin. The level ice resistance tests were performed by monitoring the air temperature until the target ice properties were estimated to have been reached. At this point, the elastic modulus and flexural strength were then measured in approximately the centre of the ice basin. When the flexural strength was at the target strength, the ice tests commenced. Following the ice tests, the flexural strength was remeasured and the ice thickness, crushing strength and other ice properties were measured.

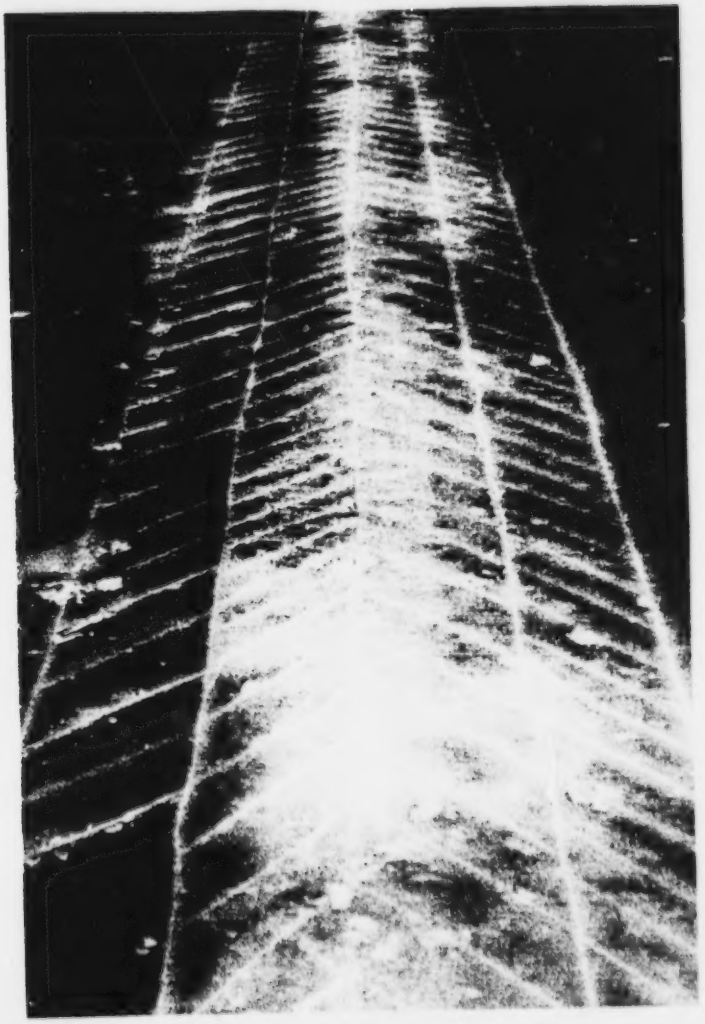
Typically all ice properties were measured at the longitudinal centre of the basin. However, if there was a localized area of poorer ice, no measurements were taken there.

The resistance tests were performed in a continuous manner unless a strength change between tests was required. The carriage drive computer was programmed to travel approximately one third of the basin at each speed. If two ice strengths were required per sheet, sufficient time was left between the two sets to permit the ice to decay to the second strength. The ice properties for each set were performed as close to the resistance test time as possible.

The pre-sawn tests (or zero ice strength tests) were performed in the same manner as the level ice resistance tests. However, prior to the test, the ice sheet was cut into a herringbone pattern as shown in Figure 3.6. The ice sheet was initially cut lengthwise at the model centreline, the quarter beam points, and approximately 10% over the maximum beam. The diagonal cuts were made at a length to breadth ratio of approximately 4:1, at an angle of approximately 45° to the centreline.

FIGURE 3.6

PRESAWN ICE SHEET



3.2 Flexural Strength Measurement

The technique used to measure the flexural strength consists of a spring scale to break a cantilever beam cut in the ice. Cantilever beam tests are performed by cutting three of the four sides of a rectangular shape, and then loading the free end until failure occurs as shown in Figure 3.7.

A beam is cut to an appropriate size using an ice saw, leaving sufficient clearance on all three sides so as not to restrict deflection. The beam is then loaded until failure and carefully removed to measure its exact dimensions.

The beams are cut to a length of five times the thickness, and a breadth of twice the thickness. Using these dimensions it is possible to neglect the effect of having the beam supported on an elastic foundation, permitting the use of 'classical beam theory'. The error caused by neglecting an elastic foundation is less than five percent if target dimensions are achieved. Therefore, the flexural strength is given by:

$$\sigma_f = 6\ PL/Bh^2 \qquad (3.1)$$

When this test is being done, typically six beams are prepared in one spot; five are failed with downward loading and one is upwardly loaded. The mean of the five strengths are treated as the strength at that point.

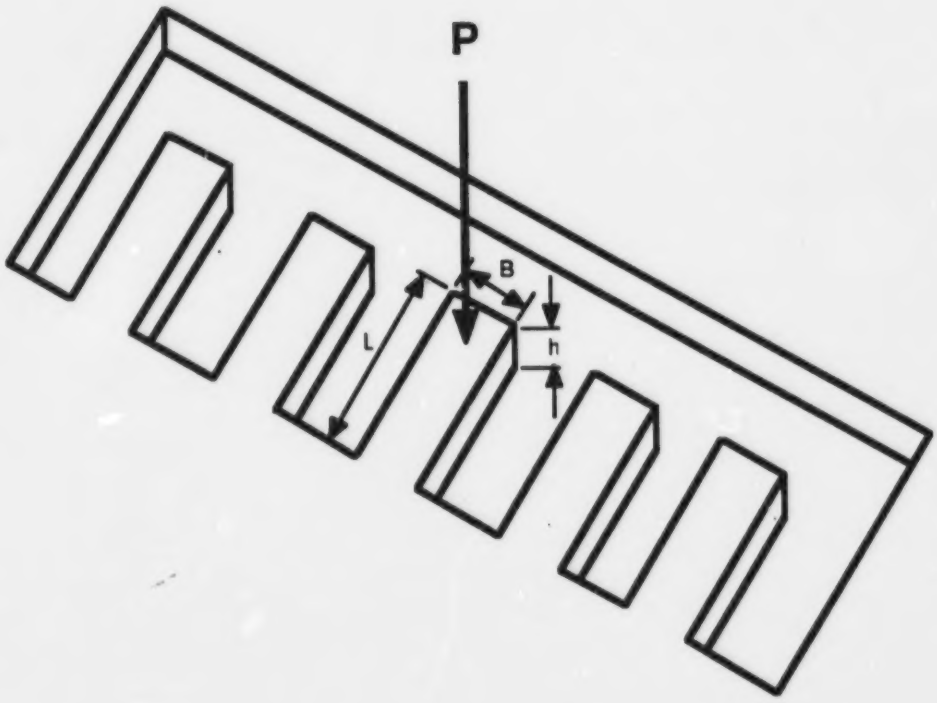
3.3 Elastic Modulus Measurements

The elastic modulus is determined by applying a load on the ice and simultaneously measuring the deflection. Ideally, the load should be a point load, but for practical reasons the load is applied to a "button". The button as well as distributing the load evenly to the ice acts as a thermal insulator between the ice sheet and the load.

The load is applied with a small dead weight set. To prevent errors caused by creep while loading the ice, the load is applied and removed in less than thirty seconds. The ice deflection is the difference between the deflection while under load and that immediately following the removal of the load, and is measured using an LVDT.

This procedure is followed using a number of different loads, and the data regressed to give the mean load/deflection ratio. The mean load/deflection ratio is then used to calculate the characteristic length as given by Sodhi [1], which is an extension of Wyman's theories for an infinite free floating plate on an elastic foundation [2]. Knowing the characteristic length, the in-plane deflection modulus can be calculated.

Figure 3.7 MEASUREMENT OF FLEXURAL STRENGTH



L ~ 5h
B ~ 2h

3.4 Fracture Toughness Measurements

The plane strain mode I pure tensile fracture toughness is obtained adjacent to and at the same time as the flexural strength. Six samples are prepared to the compact tension specimen geometry (ASTM STP 410 [3,4]), with prepared crack length typically 15 cm long. The specimen geometry is the same for all thickness, a rectangle 20 cm x 30 cm, and is failed in situ. The specimen measures the critical stress intensity factor for a crack plane oriented in the vertical, propagating horizontally. This is the fracture toughness, the resistance to crack propagation, of what is referred to as a radial crack.

3.5 Model Ice Density Measurements

As the ice sheet tempers it melts from the inside by the dopants trapped in the crystal structure as the ice is formed. For this reason the water content increases as the ice tempers and the density increases from about 0.9 at its initial strength to approximately 1.0 as the ice rots away.

The density is determined by placing a beaker of doped water on a scale. A sample of model ice is added to the beaker of water and the increased load on the scale is measured as the ice sample is submerged. The ice is then removed and measured with calipers to determine its volume. The density of the ice is calculated as follows:

$$\rho_i = \rho_w - \frac{F}{V}$$

3.6 The Uniaxial Crushing Strength Measurements

Due to the anisotropy of EG/AD/S ice, crushing strength must be measured vertically and horizontally. A small piece of ice, typically 5 cm by 5 cm by the ice thickness is placed between the plates of a press and crushed through the application of a load. The crushing strength is calculated by dividing the load by the cross sectional area.

3.7 Ice Friction Measurements

A special ice friction testing apparatus has been built at IMD. In it a plate may be pulled across a 40 cm x 30 cm piece of model ice at rates up to and beyond the testing speed of 10 cm/s recommended by the ITTC Ice Committee. The normal load is applied with dead weights, and the tangential load measured with a load cell.

3.8 Ice Thickness Measurements

The ice thickness was measured following the level ice test. Standard vernier calipers were used to measure the ice thickness on both sides of the broken channel at approximately 2 m intervals.

4. RESULTS AND DISCUSSION

The results presented here are those used for the analysis. The remainder of the data which has been reproduced from IMD's report are found in Appendix I.

4.1 Open Water Resistance

Table 4.1 lists the open water resistance measurements obtained in this program. These numbers are derived by averaging the steady state portion of the test, which typically utilized the entire length of IMD's ice tank.

Since these tests were performed only as an open water reference value for the ice tests, no turbulence stimulation devices were used. Therefore, these results are only meaningful at model scale and should not be used to predict full scale open water resistance.

Figure 4.1 shows a plot of the model scale open water resistance, with a mean logarithmic curve fitted through the data. Since only a limited number of points are available, only a first order logarithmic curve was fitted. However, this curve will be more than adequate for use with the level ice test analysis. The open water resistance can be approximated as:

$$R_{ow} = 146.1\ v^{1.597} \qquad (4.1)$$

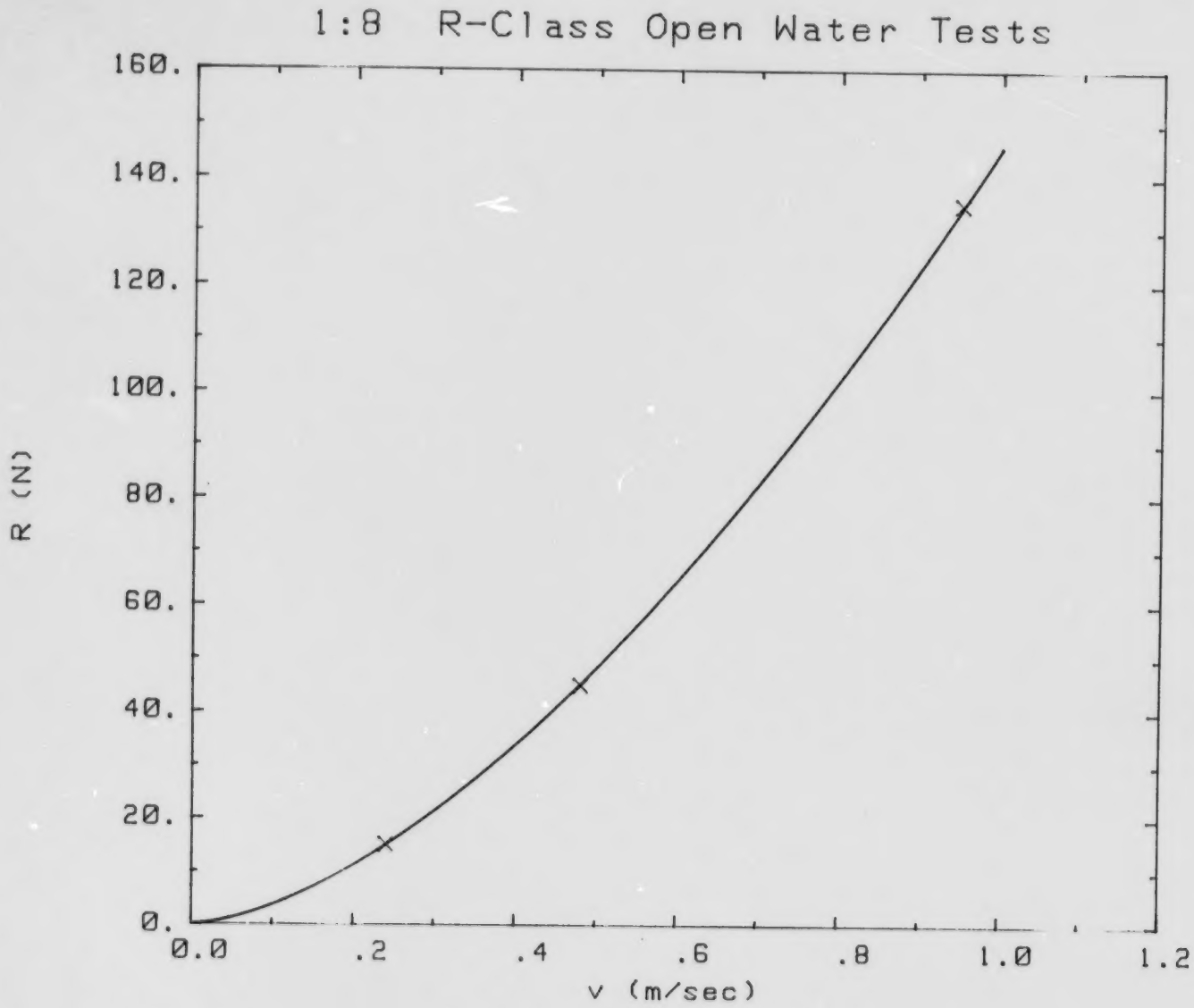
with R_{ow} = open water resistance (in Newtons)

v = model velocity (in m/sec)

TABLE 4.1
OPEN WATER RESISTANCE

MODEL SPEED (m/sec)	MEAN RESISTANCE (N)
0.24	15
0.48	45
0.95	135

FIGURE 4.1


1:8 R-Class Open Water Tests
160.
140.
120.
100.
80.
60.
40.
20.
0.
R (N)
0.0
.2
.4
.6
.8
1.0
1.2
v (m/sec)

4.2 Level Ice Resistance

The level ice resistance data is listed in Table 4.2. For each test, the average carriage speed, ice strength, ice thickness, total resistance, pitch angle and heave amplitude are given for the steady state portion of the test. The rms (root-mean-square), for the yaw load, the roll angle, the pitch angle and the heave amplitude are also given for the same time interval.

The level ice resistance data is shown in graphical form in Figure 4.2. The total resistance is plotted against the velocity, with a different symbol for each of the target ice conditions. Since there is a variation around the target conditions of upwards of 20% on ice thickness and 26% on flexural strength, this figure should only be used to deduce trends. However, even looking at target conditions, the data looks quite good and follows the trends of typical icebreaking resistance data.

The data was then regressed into the typical icebreaking resistance equation format of:

$$R_T = R_I + R_{ow} \tag{4.2}$$

where R_T = total resistance
R_I = icebreaking resistance
R_{ow} = open water resistance

The conventional manner is to use the measured open water resistance and subtract it from the total resistance to produce a predictor equation with only icebreaking terms. However, this approach assumes that the open water term is unaffected by the presence of ice: which is not correct.

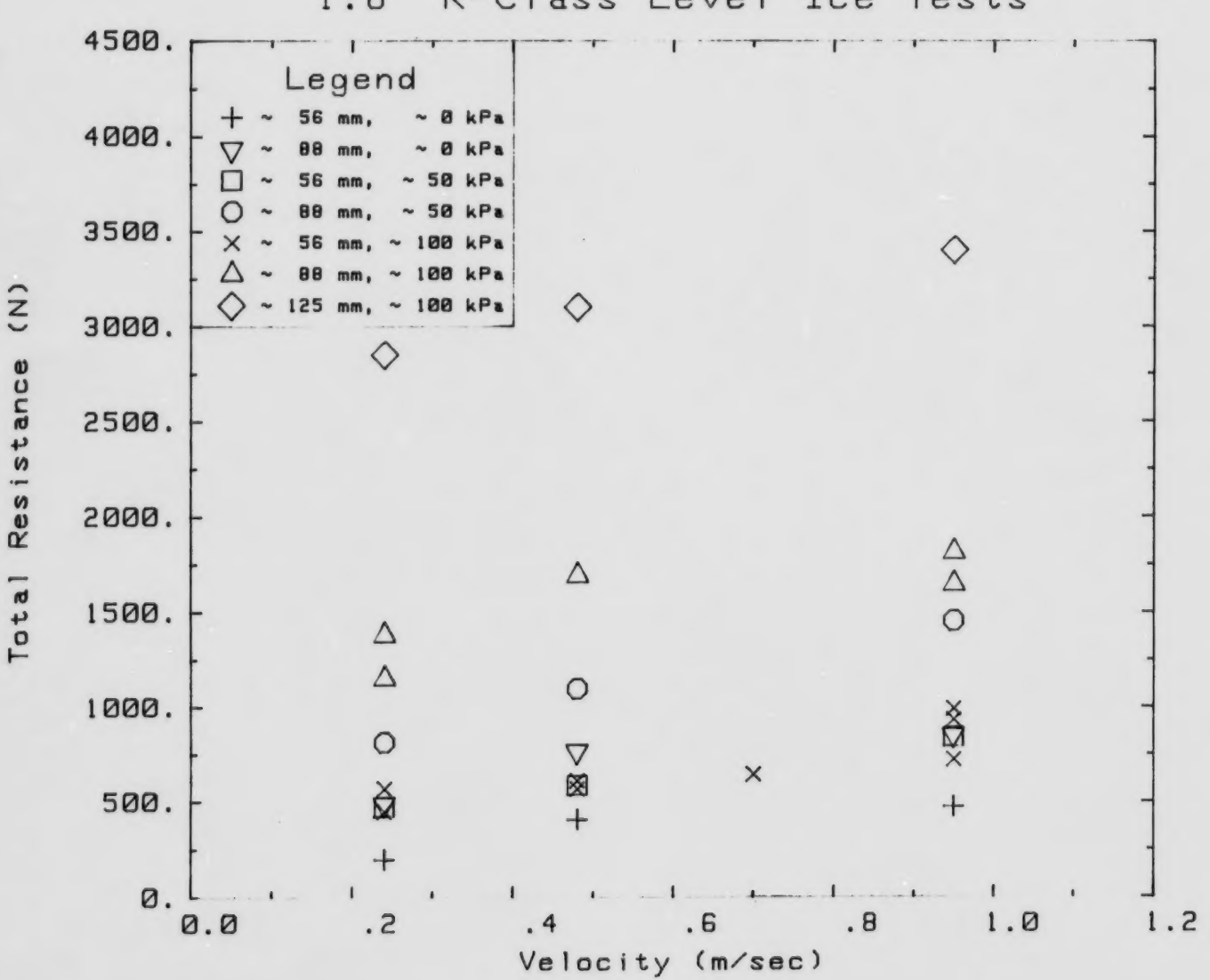
From the hydrodynamics point of view, the open water resistance is comprised of two major terms; the wave making resistance and the skin frictional resistance. These terms are usually analyzed separately in model testing since the frictional resistance is a function of Reynold's number and the wave making resistance is a function of Froude's number. To scale both of these terms at the same time is not practical.

The wave making resistance is the portion of the total open water resistance which goes into the creation of waves. However in ice, the free surface is suppressed and therefore, the propagation of waves is suppressed. The effect of suppressing the free surface on the open water wave making resistance is not known, however, it is expected to increase the hydrodynamic resistance because of an increased pressure field surrounding the hull caused by the presence of the ice.

TABLE 4.2 - 1:8 R-CLASS LEVEL ICE RESULTS

Ice Sheet No.	Model Speed (m/s)	Ice Strength (kPa)	Ice Thickness (mm)	Mean Resistance (N)	Yaw Load (N rms)	RMS Roll Amplitude (deg)	Pitch Amplitude (deg)		Heave Amplitude (mm)	
							Steady	RMS	Steady	RMS
1	0.48	0.	55.1	404.	507.	0.1	0.1	0.1	2.1	2.4
1	0.48	95.	54.4	610.	1046.	0.2	0.1	0.1	1.9	2.2
1	0.48	95.	53.4	567.	1241.	0.1	0.1	0.1	1.7	1.9
2	0.95	98.	55.5	931.	1908.	0.2	0.2	0.0	0.1	1.3
2	0.24	98.	54.4	566.	792.	0.3	0.1	0.1	3.0	3.2
2	0.24	63.	56.3	471.	600.	0.3	0.1	0.1	2.9	1.8
3	0.24	116.	90.5	1380.	1726.	0.7	0.3	0.1	12.0	4.9
3	0.48	116.	90.6	1690.	1654.	0.6	0.4	0.1	11.0	2.8
3	0.48	0.	88.0	766.	569.	0.2	0.1	0.1	3.5	2.2
4	0.95	90.	88.6	1643.	3053.	0.3	0.4	0.1	6.3	4.3
4	0.24	0.	89.2	487.	206.	0.1	0.1	0.0	2.3	0.9
4	0.24	48.	88.7	813.	864.	0.5	0.2	0.1	6.0	2.3
5	0.48	48.	90.4	1098.	1930.	0.4	0.2	0.1	8.5	3.5
5	0.95	48.	88.3	1453.	2979.	0.3	0.2	0.0	1.1	4.6
5	0.95	0.	87.9	851.	318.	0.2	0.1	0.0	-0.2	1.5
6	0.48	56.	57.4	587.	1017.	0.1	0.2	0.0	3.4	2.9
6	0.95	56.	58.0	842.	1346.	0.2	0.1	0.0	-3.5	2.6
6	0.95	0.	55.2	472.	155.	0.1	0.1	0.0	-5.0	2.4
7	0.24	111.	134.1	2850.	2718.	0.9	0.8	0.2	23.4	4.9
7	0.48	111.	134.6	3100.	2834.	0.8	0.9	0.3	23.3	6.5
7	0.95	111.	129.4	3400.	3413.	0.4	0.8	0.1	19.7	5.2
8	0.95	90.	55.9	990.	1913.	0.3	0.1	0.0	-0.6	2.9
8	0.24	0.	54.0	193.	130.	0.1	0.0	0.0	0.8	1.0
9	0.24	90.	90.1	1149.	1478.	0.6	0.4	0.1	9.9	2.7
9	0.95	90.	88.8	1810.	3046.	0.6	0.4	0.1	6.1	4.2
10	0.70	91.	47.0	643.	777.	0.1	0.1	0.0	1.9	2.4
10	0.95	91.	47.3	721.	1437.	0.2	0.1	0.0	-4.2	2.2
10	0.24	91.	44.4	446.	576.	0.2	0.1	0.0	2.1	3.4

FIGURE 4.2


1:8 R-Class Level Ice Tests
Legend
+ ~ 56 mm, ~ 0 kPa
▽ ~ 88 mm, ~ 0 kPa
□ ~ 56 mm, ~ 50 kPa
○ ~ 88 mm, ~ 50 kPa
× ~ 56 mm, ~ 100 kPa
△ ~ 88 mm, ~ 100 kPa
◇ ~ 125 mm, ~ 100 kPa
Total Resistance (N)
4500.
4000.
3500.
3000.
2500.
2000.
1500.
1000.
500.
0.
0.0
.2
.4
.6
.8
1.0
1.2
Velocity (m/sec)

The open water skin frictional resistance is the portion of the total open water resistance which is influenced by the boundary layer. In open water resistance testing, turbulence stimulators are used to create a correct boundary layer. However during ice tests, turbulence stimulators cannot be used. It is thought that the presence of the ice will vary the boundary layer anyway. Regardless, the boundary layer in ice is different than in open water. Therefore, the skin frictional resistance will be different.

Therefore, if the open water resistance term in ice is not the same as in open water, then it is not correct to simply remove the hydrodynamic resistance as is typically done. To circumvent this problem, the approach adopted is to perform the regression analysis on the total resistance, but include hydrodynamic terms. The ice resistance is typically expressed as:

$$R_I = C_o + C_1 h^{n1} + C_2\, vh^{n2} + fn\,(\sigma_f h^{n3} \text{ or } \sigma_f v) \qquad (4.3)$$

and the open water resistance is typically expressed as:

$$R_{ow} = C_o + C_1 v^1 + C_2 v^2 + C_3 v^3 + \ldots \qquad (4.4)$$

or as was found for the open water tests given in Section 4.1:

$$R_{ow} = C_1 v^{n1} \qquad (4.5)$$

Therefore combining all these terms, a stepwise regression was formed on:

$$R_T = fn(v, \sigma_f, h, h^{1.5}, vh^2, \sigma_f h, \sigma_f h^2, \sigma_f v, v^2, v^3, v^{1.597}) \qquad (4.6)$$

The output of the stepwise regression is given in Appendix II. Without any manual intervention, the resistance predictor equation is of the form:

$$R_T = C_o + C_1 h + C_2 vh^{1.5} + C_3 \sigma h^2 + C_4 \sigma_f v \qquad (4.7)$$

with a standard error of 69.9 N.

Since this equation has two ice strength terms which are not usually found together, the one with the poorer correlation was manually dropped. With the '$\sigma_f v$' term dropped, the correlation of all terms which included velocity increase. The term with the highest correlation which would fit into the form of equations 4.2 to 4.5 was manually added. The resulting equation is:

$$R_T = -58.2 + 4432h + 18\,810vh^{1.5} + 1022\sigma_f h^2 + 200.7v^{1.597} \quad (4.8)$$

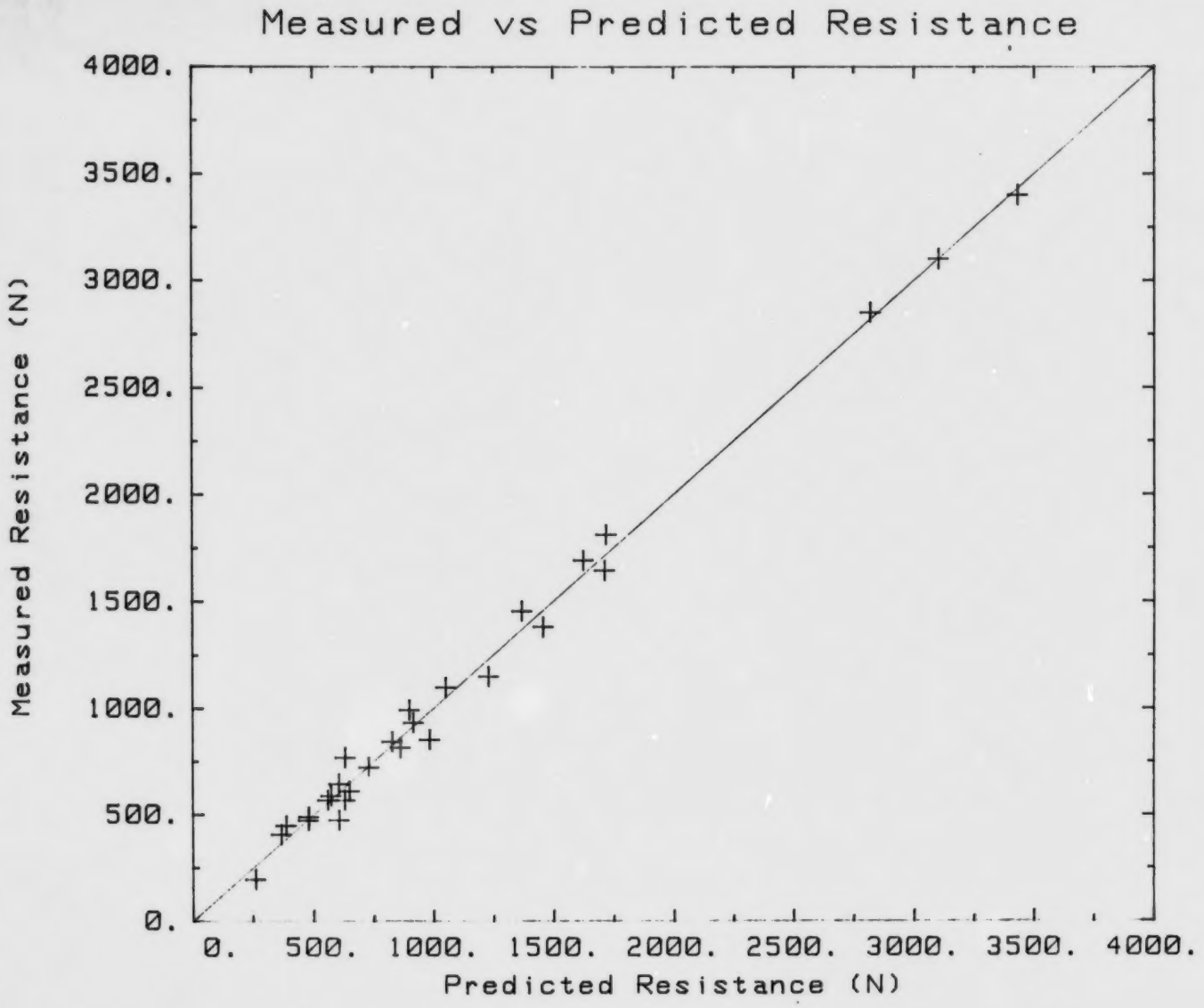
which has a standard error of 72.9 N where:

R_T = total resistance (in N)
h = ice thickness (in m)
v = model velocity (in m/sec)
σ = flexural strength (in kPa)

Figure 4.3 shows that this equation fits the data quite well. Some quality of fit plots are included in Appendix II showing both the error and percentage error in this equation as a function of ice thickness, ice strength and model velocity. From the quality of fit diagrams, the error does not appear to be a function of ice thickness, strength or velocity. Therefore, it appears that equation 4.8 fits the data reasonably well without any additional thickness, strength and velocity influence. However, the quality of fit plots do show that there is considerably more scatter in the pre-sawn tests (the tests at a strength of 0 kPa) than in the level ice tests. Although the scatter for the pre-sawn tests is larger than the level ice tests, the mean error is still approximately zero. Therefore, including the pre-sawn test data in the level ice regression analysis will still produce good results.

Separating the icebreaking components and the open water components out of equation 4.8 produces an open water resistance term in level ice which is approximately 37.4% larger than measured in open water. This discrepancy could be caused by hiding the random nature of the icebreaking phenomenon into this velocity term. However, these results do not support the approach taken by most other model ice testing facilities, in which the open water resistance is subtracted from the total resistance to give the resistance in ice.

FIGURE 4.3


Measured vs Predicted Resistance
Measured Resistance (N)
4000.
3500.
3000.
2500.
2000.
1500.
1000.
500.
0.
0. 500. 1000. 1500. 2000. 2500. 3000. 3500. 4000.
Predicted Resistance (N)

4.3 Broken Piece Size

Appendix III shows the photographs used to collect the broken piece size data and a tabulation of the individual floes. The broken piece size data is summarized in Table 4.3.

This data was extracted from pictures taken from a hand held camera, and as such the scaling of the floes is not accurate. The scaling was achieved by measuring the mean channel width from the picture at the point of each floe, and assuming the channel was 10% larger than the breadth of the model. The floe dimensions measured on the picture are then scaled linearly in the same ratio as the channel width. Although this approach is not as precise as having a fixed camera and photographing a scaled grid, the results are still quite useful.

The measurements obtained from each floe are its length, width and area. The length and width listed are those of an equivalent rectangle: the length being the largest dimension and the width being perpendicular to the length. The area of the floe is simply the product of length and the width.

The photographs were taken of the final 'footprint' the model left in the level ice in a similar way to the tests carried out with the KIRORIAK in urea and synthetic model ice. Following each test, the ice carriage was run backwards approximately 1 meter. As the carriage reversed, the ice floes, that had been submerged by the bow of the model, surfaced. These are the floes in which the photograph was taken. Therefore, all floes were the result of the primary breaking.

As observed in urea ice, these floes had numerous cracks through them as shown in Figures 4.4 and 4.5. Although these cracks were quite obvious, the floes did not fail at these cracks. Even after passing under the hull, there was sufficient residual strength at these cracks that most floes remained intact. The dimensions listed are of the intact floe. If the floes had failed at these cracks, the broken piece size would have been better.

Figures 4.6, 4.7 and 4.8 show plots of the floe dimensions versus ice thickness and strength. The average dimension is shown along with an error band of the standard deviation. The piece size either remains constant or tends to decrease. Although there is a considerable error band associated with this data, the floe size does not appear to increase with ice strength as Tatinclaux [5, 6] suggests.

The data from [5,6 and 7] was plotted in non-dimensional form in [5]. The same data is shown in Figures 4.9 and 4.10 with the present data set included. Mean regression lines for synthetic ice and urea ice were also included.

TABLE 4.3

SUMMARY OF BROKEN PIECE SIZE DATA

Test No.	Ice Thickness (mm)	Ice Strength (kPa)	Floe Length (m)		Floe Width (m)		Floe Area (m^2)		Number of Floes
			Aver	Std dev	Aver	Std dev	Aver	Std dev	
2- 2	54.4	98	0.406	0.253	0.199	0.114	0.0915	0.0863	33
3- 2	90.6	116	0.536	0.486	0.170	0.095	0.1216	0.1352	49
4- 1	88.6	90	0.656	0.469	0.182	0.090	0.1445	0.1496	24
5- 2	88.3	48	0.813	0.625	0.283	0.143	0.2767	0.3099	17
6- 2	57.4	56	0.650	0.282	0.183	0.091	0.1282	0.1108	34

FIGURE 4.4

CRACKS PROPAGATING IN FRONT OF MODEL DURING TEST 4-1

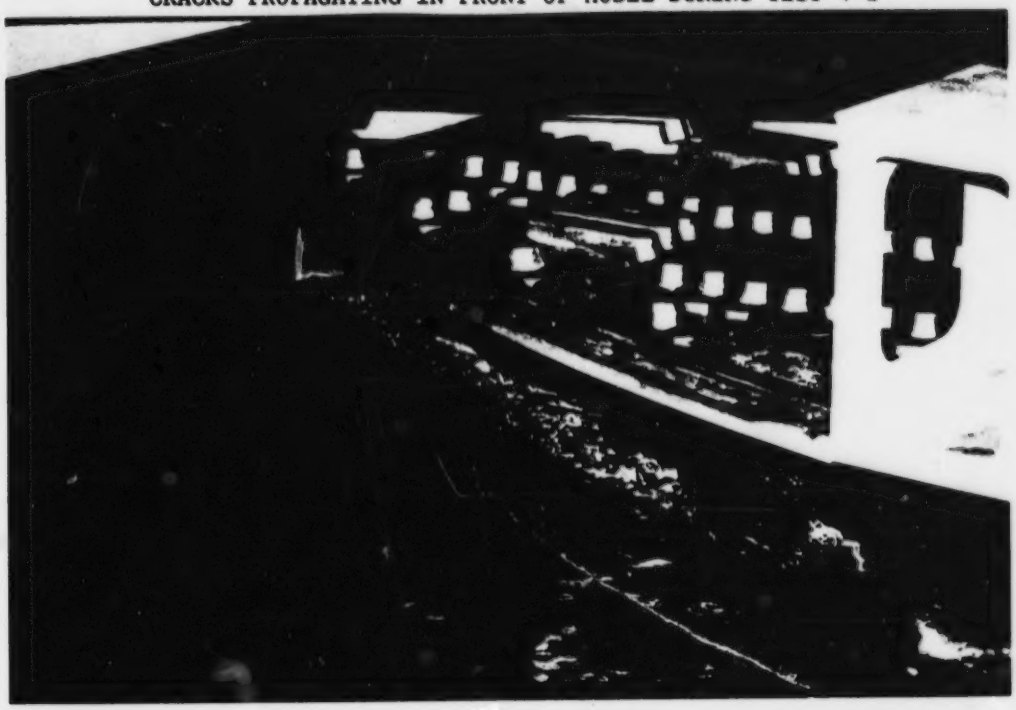


FIGURE 4.5

CRACKS OBSERVED IN FLOES FOLLOWING TEST 6-2

FIGURE 4.6

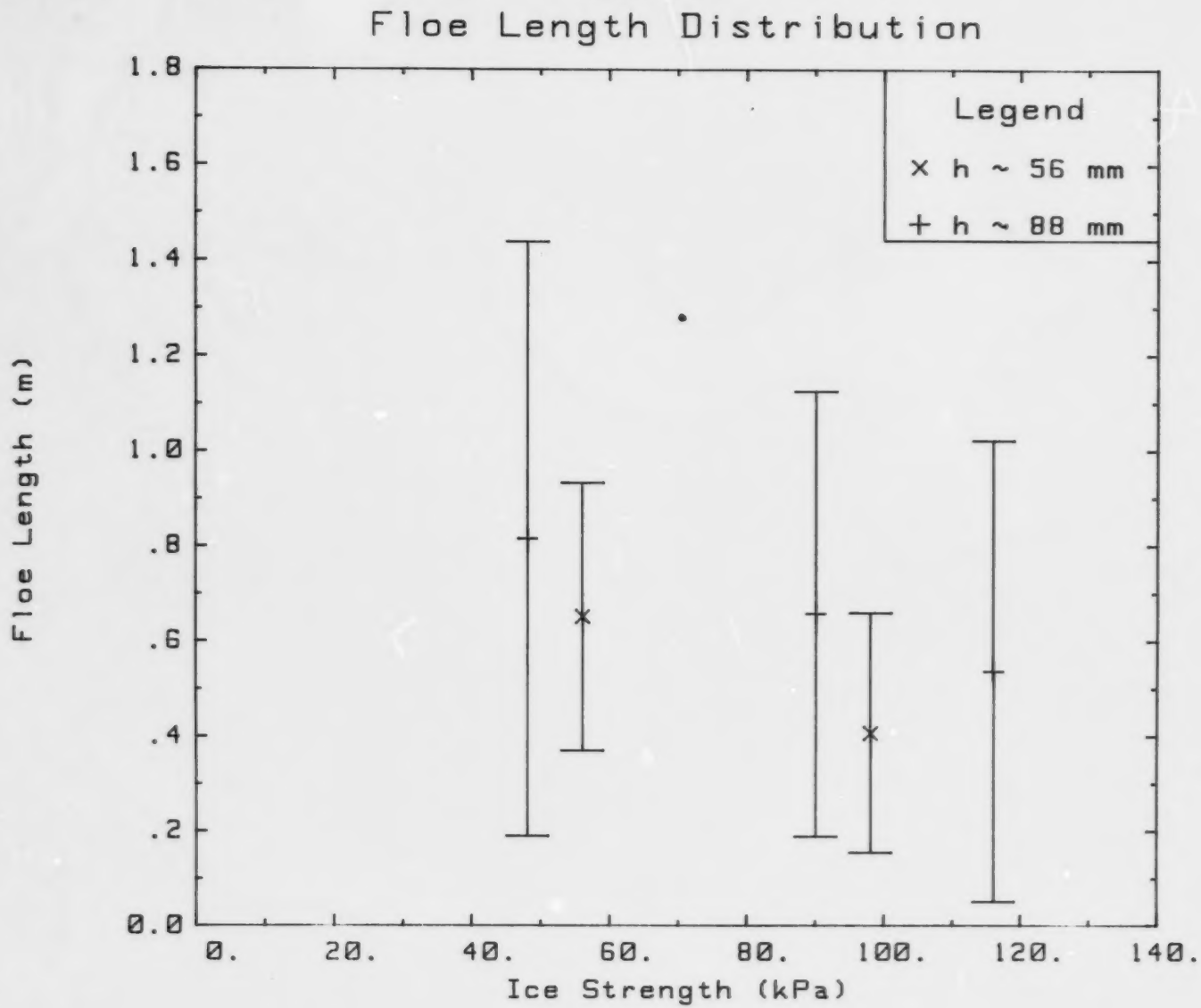

Floe Length Distribution
Legend
× h ~ 56 mm
+ h ~ 88 mm
Floe Length (m)
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0.0
0.
20.
40.
60.
80.
100.
120.
140.
Ice Strength (kPa)

FIGURE 4.7

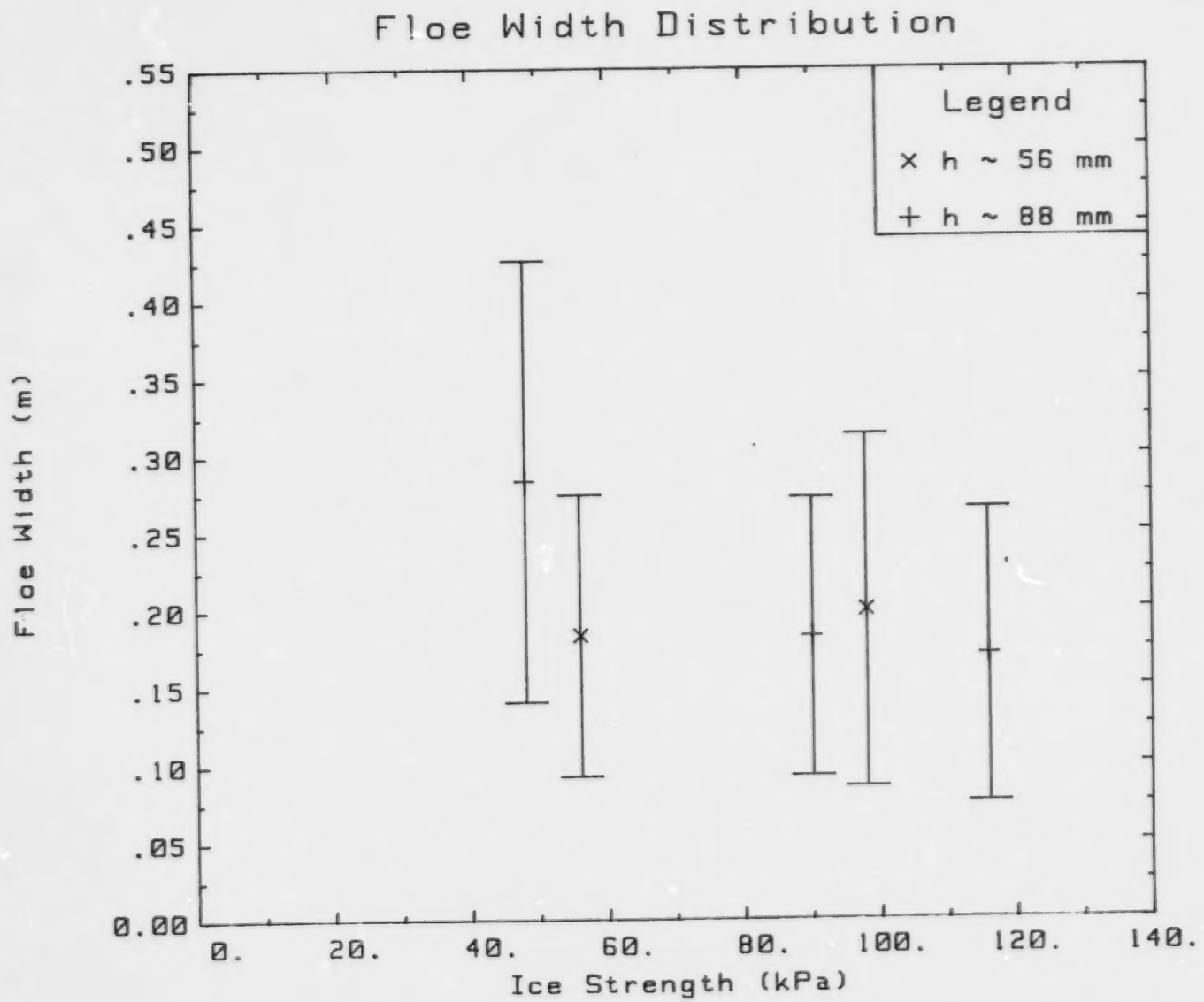

Floe Width Distribution
Legend
× h ~ 56 mm
+ h ~ 88 mm
Floe Width (m)
.55
.50
.45
.40
.35
.30
.25
.20
.15
.10
.05
0.00
0.
20.
40.
60.
80.
100.
120.
140.
Ice Strength (kPa)

FIGURE 4.8

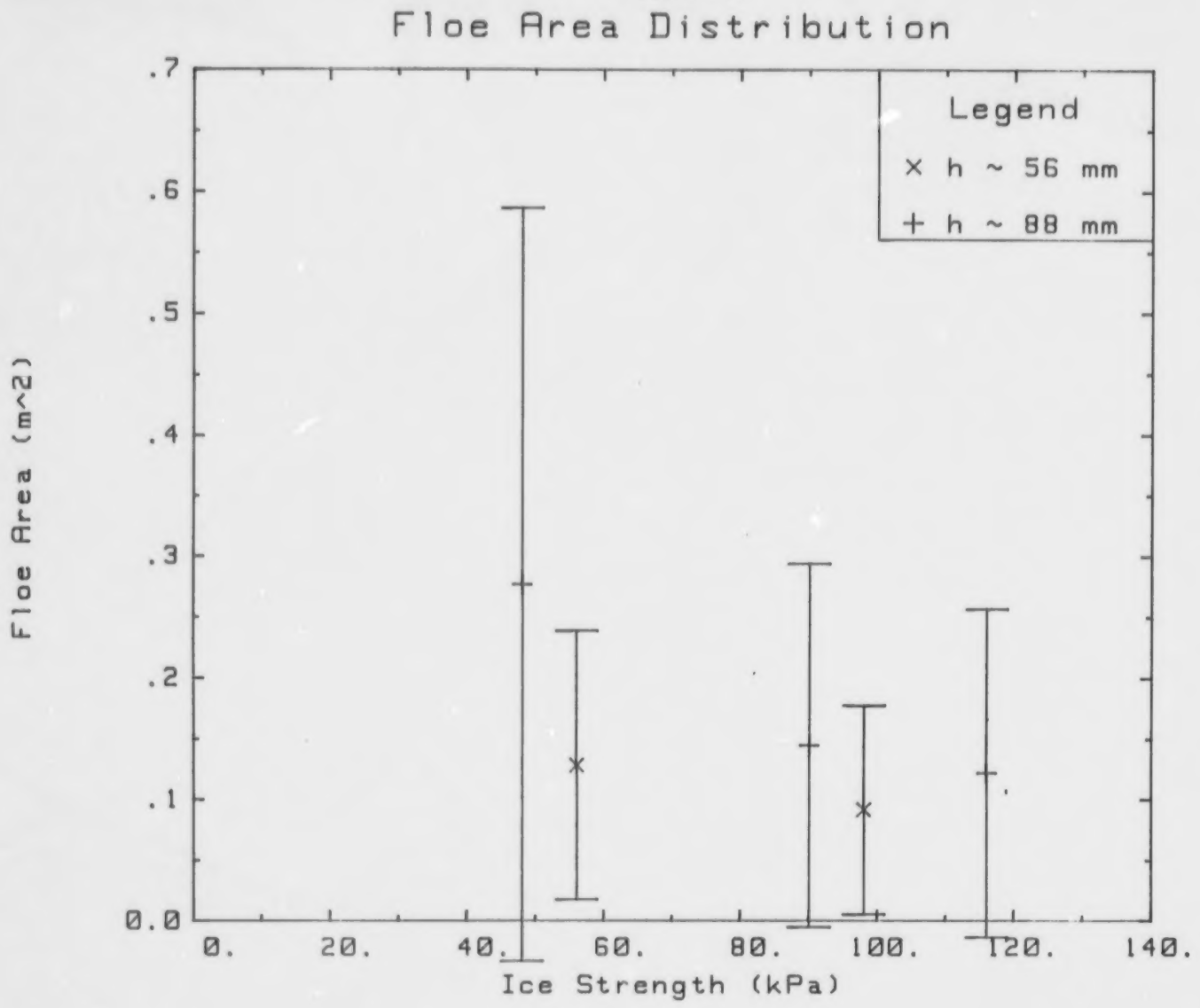

Floe Area Distribution
Legend
× h ~ 56 mm
+ h ~ 88 mm
Floe Area (m^2)
.7
.6
.5
.4
.3
.2
.1
0.0
0.
20.
40.
60.
80.
100.
120.
140.
Ice Strength (kPa)

FIGURE 4.9

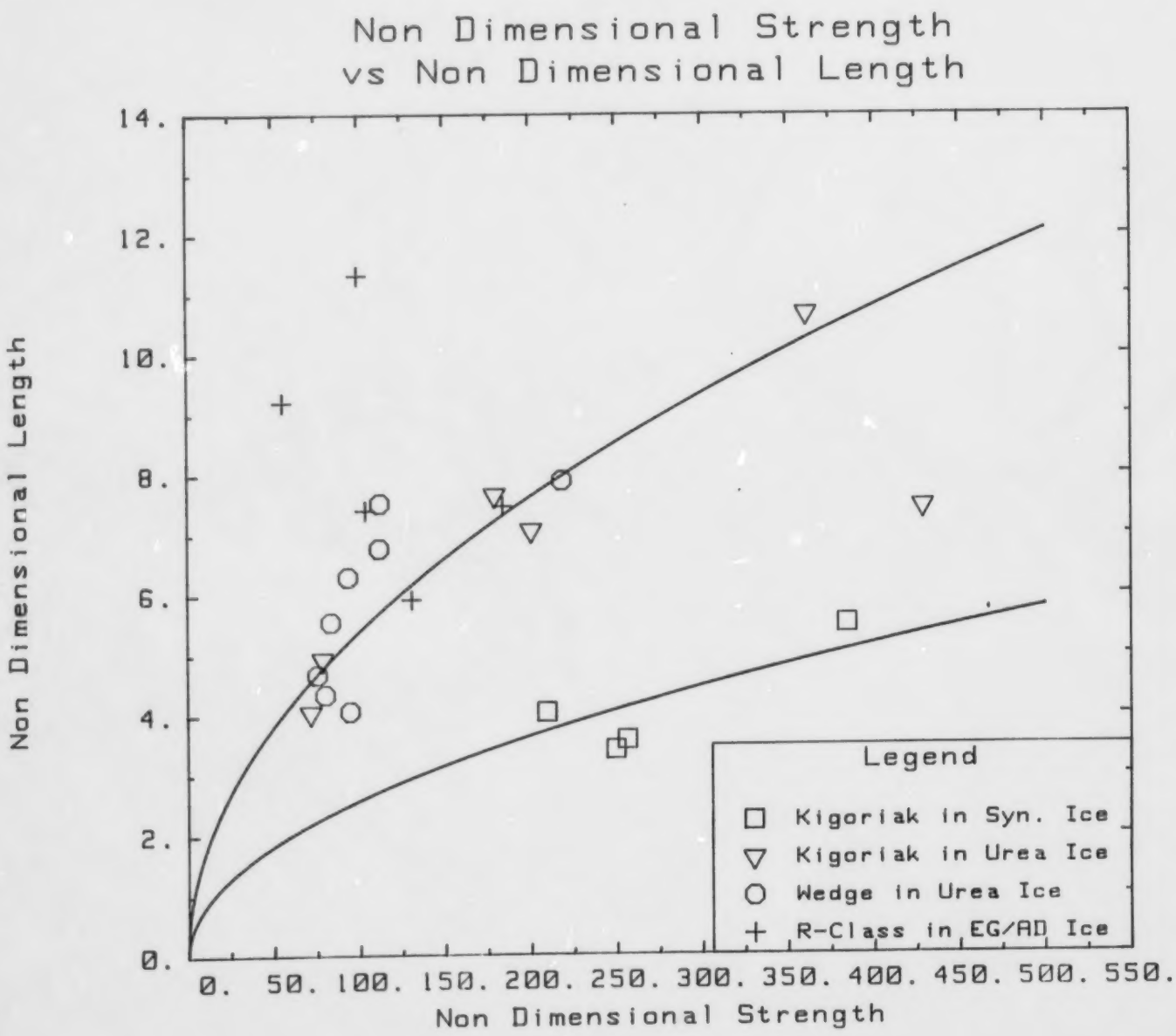
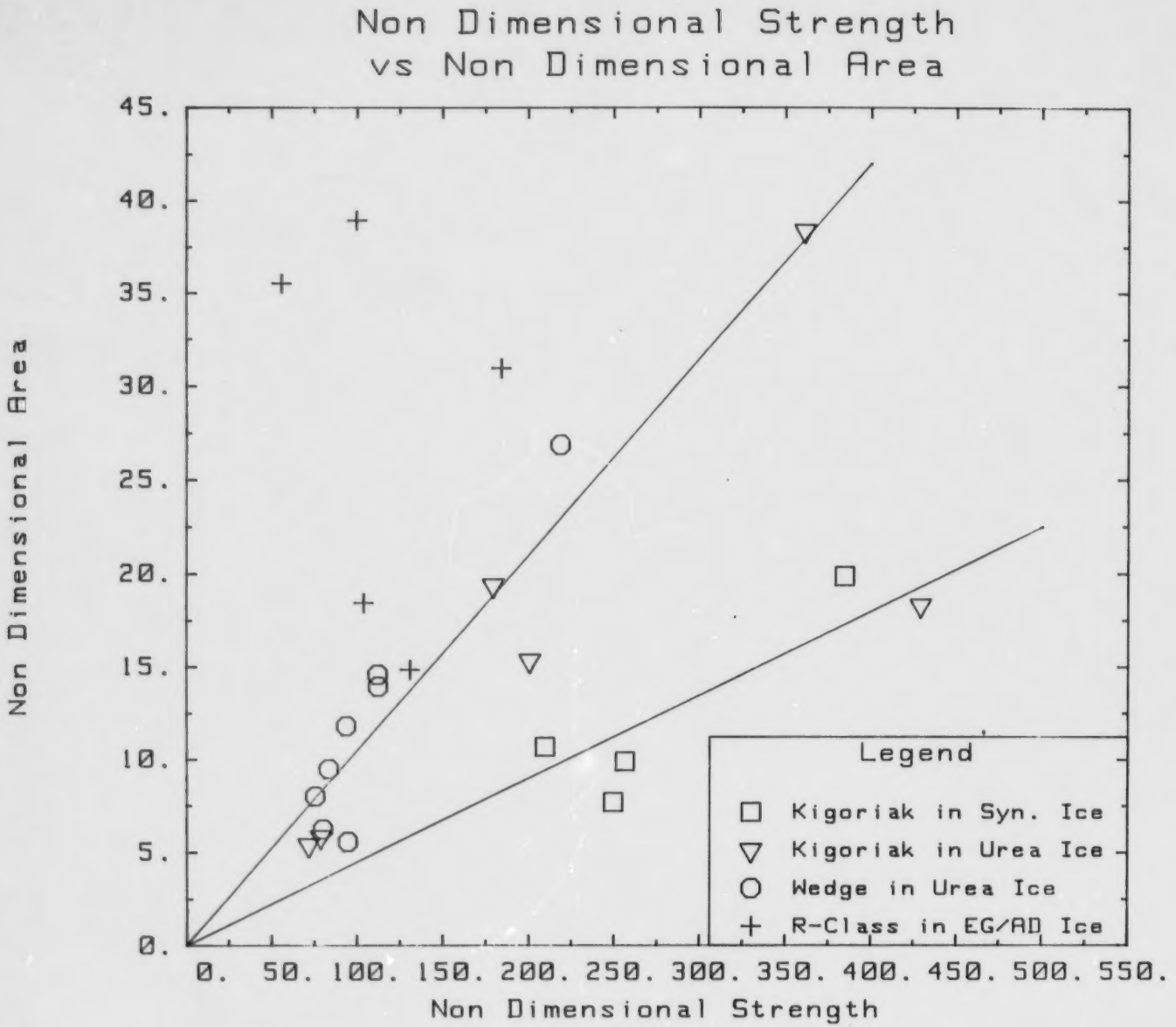

Non Dimensional Strength
vs Non Dimensional Length
Non Dimensional Length
Non Dimensional Strength
0.
2.
4.
6.
8.
10.
12.
14.
0. 50. 100. 150. 200. 250. 300. 350. 400. 450. 500. 550.
Legend
Kigoriak in Syn. Ice
Kigoriak in Urea Ice
Wedge in Urea Ice
R-Class in EG/AD Ice

FIGURE 4.10


Non Dimensional Strength
vs Non Dimensional Area
Non Dimensional Area
45.
40.
35.
30.
25.
20.
15.
10.
5.
0.
0. 50. 100. 150. 200. 250. 300. 350. 400. 450. 500. 550.
Non Dimensional Strength
Legend
Kigoriak in Syn. Ice
Kigoriak in Urea Ice
Wedge in Urea Ice
R-Class in EG/AD Ice

4.4 Ice Friction

There are two approaches which are typically used when analyzing dynamic ice friction data. The first approach is to simply divide the tangential force by the normal force for each measurement and then average a set of measurements together to give the mean friction factor for that test condition.

The second approach is to use linear regression to calculate the slope of the mean line. Although ideally, these two methods are identical, in practice these two methods produce different results.

Figure 4.11 shows a plot of the tangential (or friction) force against the normal force. This data clearly shows a linear trend. However, there is a slight zero offset to the data.

This zero offset is typical of ice friction test results and is commonly caused by the test apparatus. Although it is not known what caused this offset in these results, if the first method is used to calculate the friction factor, the results will be affected by the zero offset. If the second method is used, the zero offset will not influence the results.

The second method is used to calculate the friction coefficient from the raw data in Appendix I. This data and the results are listed in Table 4.4. As can be seen in Table 4.4, the zero offset is significant in some of these tests.

There were three different conditions tested throughout this program. These conditions are: dry top, wet top and wet side.

The dry tests were simply measuring the friction factor of the ice surface pulled over the friction plank without a fluid boundary layer. The wet tests had a fluid boundary layer between the ice and the friction plank. For the 125 mm ice sheet, there was sufficient ice thickness to be able to measure the friction factor of the ice on its side. Therefore, for the thick ice sheet, it was possible to get additional data.

The linear regression results given in Table 4.4 are plotted against flexural strength in Figure 4.12. Also included is a mean linear regression line for the wet tests performed on the top surface of the ice. From this figure it appears that within experimental accuracy, the wet top, the dry top and the wet side friction factors are all essentially the same.

FIGURE 4.11

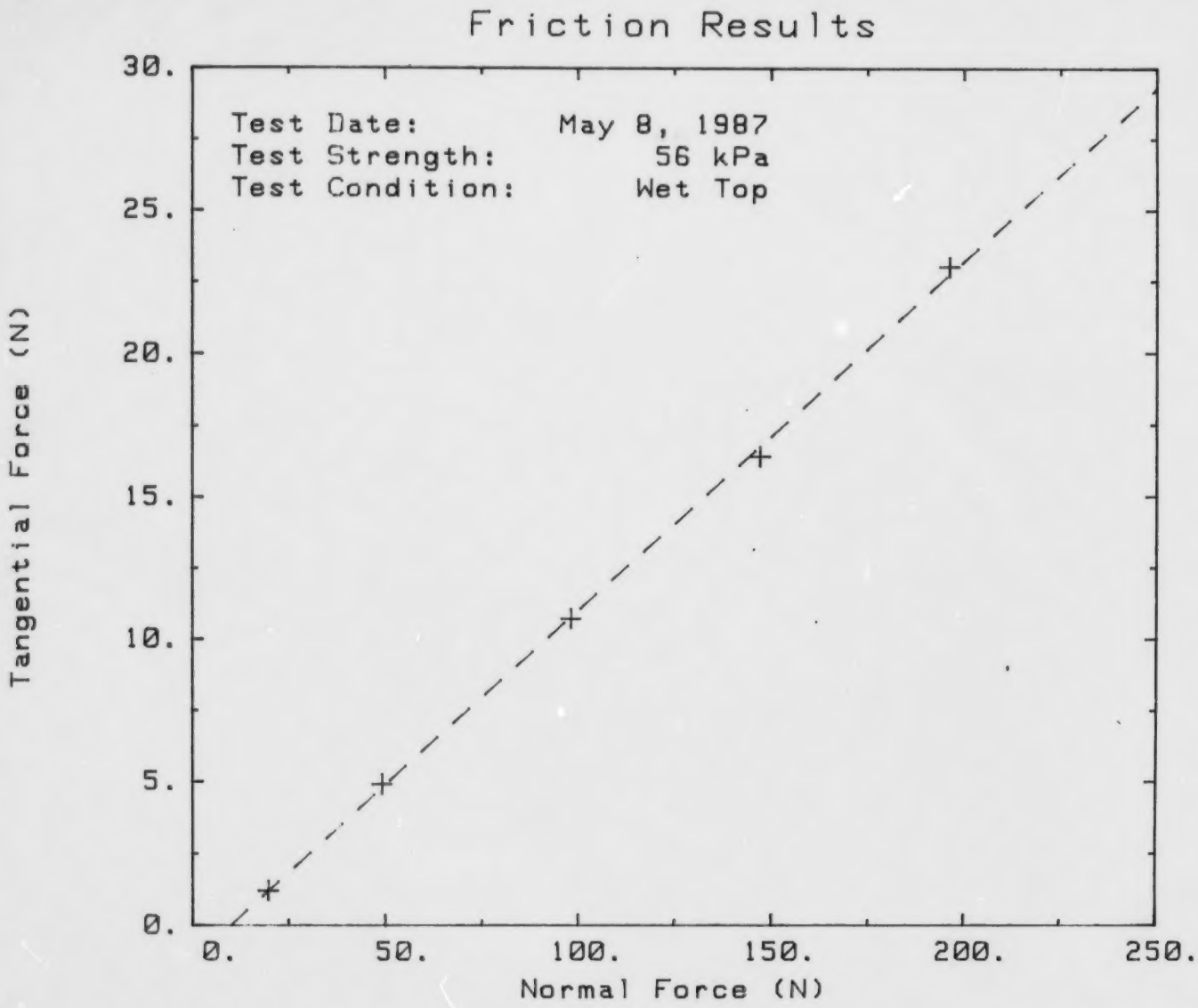
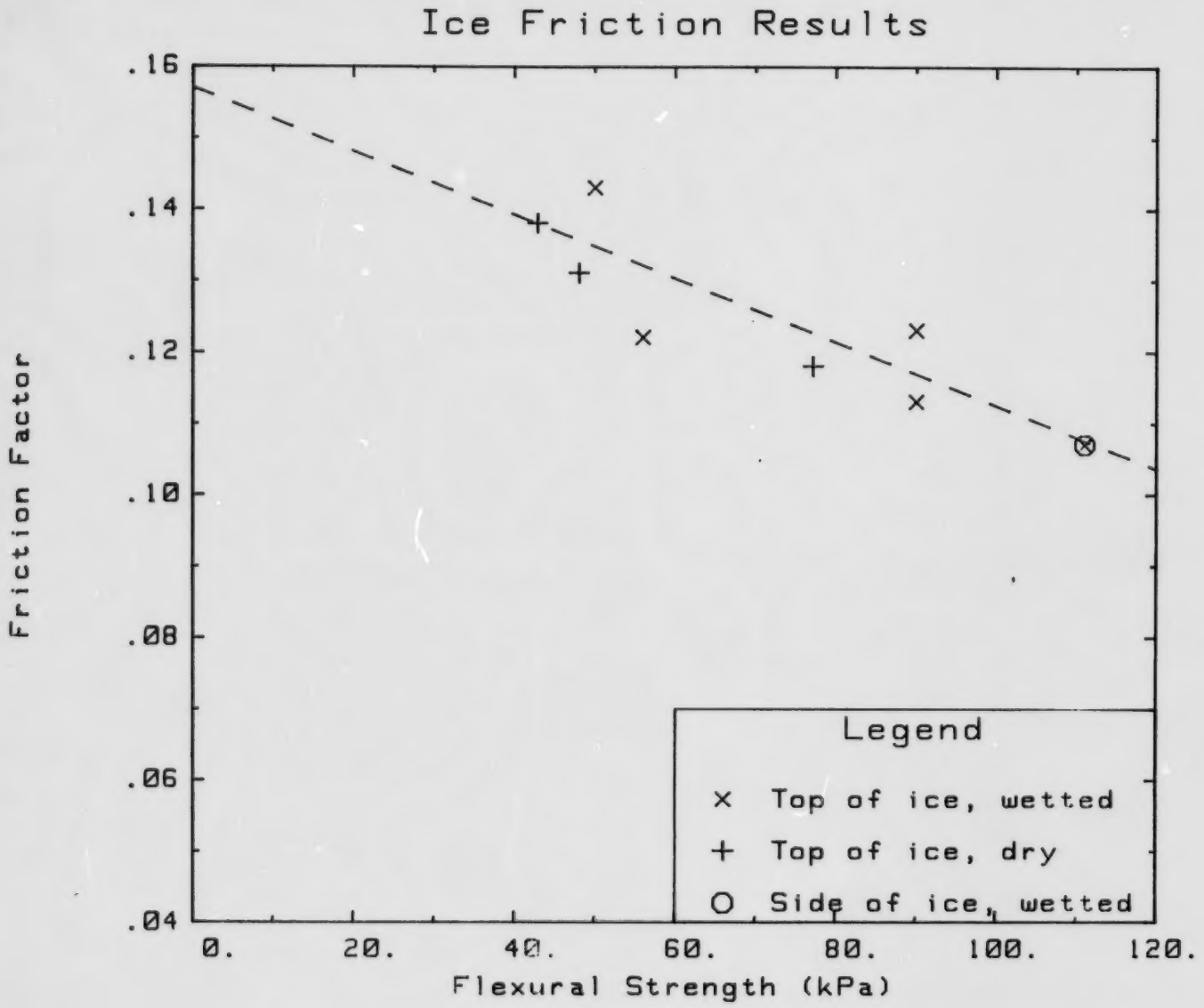

Friction Results
Test Date: May 8, 1987
Test Strength: 56 kPa
Test Condition: Wet Top
Tangential Force (N)
Normal Force (N)
0.
5.
10.
15.
20.
25.
30.
0.
50.
100.
150.
200.
250.

TABLE 4.4

ICE FRICTION RESULTS

DATE	Ice Strength (kPa)	Condition	Normal Force (N)	Tangential Force (N)	Linear Regression Results
May 08 1987	56	Dry Top	19.6	1.6	Offset= -1.523
			49.1	4.5	μ= 0.131
			98.1	11.1	Corr= 0.9986
			147.2	17.2	
			196.2	24.6	
May 08 1987	56	Wet Top	19.6	1.2	Offset= -1.221
			49.1	4.9	μ= 0.122
			98.1	10.7	Corr= 0.9997
			147.2	16.4	
			196.2	23.0	
May 08 1987	50	Dry Top	19.6	1.1	Offset= -1.253
			49.1	5.2	μ= 0.138
			98.1	12.9	Corr= 0.9974
			147.2	19.8	
			196.2	24.9	
May 08 1987	50	Wet Top	19.6	0.9	Offset= -2.209
			49.1	4.3	μ= 0.143
			98.1	12.0	Corr= 0.9995
			147.2	18.9	
			196.2	25.8	
May 12 1987	111	Wet Top	19.6	3.0	Offset= 1.333
			49.1	6.4	μ= 0.107
			98.1	12.8	Corr= 0.9969
			147.2	17.3	
			196.2	21.8	
May 12 1987	111	Wet Side	19.6	4.9	Offset= 1.568
			49.1	6.0	μ= 0.108
			98.1	11.3	Corr= 0.9932
			147.2	17.6	
			196.2	23.3	
May 14 1987	90	Dry Top	19.6	6.5	Offset= 4.472
			49.1	10.5	μ= 0.118
			98.1	16.2	Corr= 0.9997
			147.2	21.9	
			196.2	27.5	
May 14 1987	90	Wet Top	19.6	4.9	Offset= 2.472
			49.1	8.5	μ= 0.123
			98.1	14.6	Corr= 0.9999
			147.2	20.3	
			196.2	26.7	
May 25 1987	90	Wet Top	19.6	0.9	Offset= -1.706
			49.1	3.4	μ= 0.113
			98.1	9.4	Corr= 0.9993
			147.2	15.0	
			196.2	20.6	

FIGURE 4.12


Ice Friction Results
.16
.14
.12
.10
.08
.06
.04
Friction Factor
0.
20.
40.
60.
80.
100.
120.
Flexural Strength (kPa)
Legend
Top of ice, wetted
Top of ice, dry
Side of ice, wetted

5. COMPARISON WITH OTHER DATA BASES

5.1 Comparison with Full Scale Data

Before being able to compare this model resistance data with full scale data, the model resistance equation must be properly scaled. Simple Froude scaling is used as follows:

$$(R_T)_{F.S.} = \lambda^3 (R_T)_{M.S.}/1000 \tag{5.1}$$

$$H = \lambda h \tag{5.2}$$

$$V = \lambda^{1/2} v \tag{5.3}$$

$$(\sigma_f)_{F.S.} = \lambda (\sigma_f)_{M.S.} \tag{5.4}$$

where λ = scale factor

$(R_T)_{F.S.}$ = full scale total resistance (in kN)

$(R_T)_{M.S.}$ = model scale total resistance (in N)

H = full scale ice thickness (in m)

h = model scale ice thickness (in m)

V = full scale velocity (in m/sec)

v = model scale velocity (in m/sec)

$(\sigma_f)_{F.S.}$ = full scale flexural strength (in kPa)

$(\sigma_f)_{M.S.}$ = model scale flexural strength (in kPa)

Therefore, equation 4.8 can be rewritten as follows:

$$(R_T)_{F.S.} = -29.8 + 283.6\,H + 150.5\,VH^{1.5} + 1.0224\,\sigma_f H^2 + 19.53\,V^{1.597} \tag{5.5}$$

However, full scale resistance cannot be measured and total shaft thrust is all that is available. To convert resistance to thrust, a thrust deduction factor for that particular ship must be known. From work done by Bulat and Glen [8], the full scale thrust deduction factor in ice for the R-Class can be approximated as:

$$t = .05 + .0186\,V \tag{5.6}$$

Therefore, the full scale thrust predictor equation is:

$$(T)_{F.S.} = (-\ 29.8 + 283.6\ H + 150.5\ VH^{1.5} + 1.0224\ \sigma_f\ H^2 + 19.53\ V^{1.597})/(.95 - .0186\ V) \qquad (5.7)$$

Figure 5.1 shovs some full scale data from both the CCGS SIR JOHN FRANKLIN and the CCGS PIERRE RADISSON. Also shown in this figure is the predicted thrust derived from the model tests using equation 5.7.

The full scale data is only in its rav form. No correction for snov cover or deviations from the mean thickness and strength has been made. Therefore, the comparison in some cases is rather poor. The FRANKLIN data for example, has anywhere between 8 and 52 cm of snov cover. If the two FRANKLIN data points with the most amount of snov cover are removed, then the model equation falls in the middle of the full scale data.

Examining the thin ice thickness in the RADISSON trials where there is no snov cover, the agreement is excellent. The data point with the poorest fit is also in the thinnest ice.

The thicker RADISSON data has varying degrees of snov cover. However, this data also agrees reasonably well with the model predictor equation.

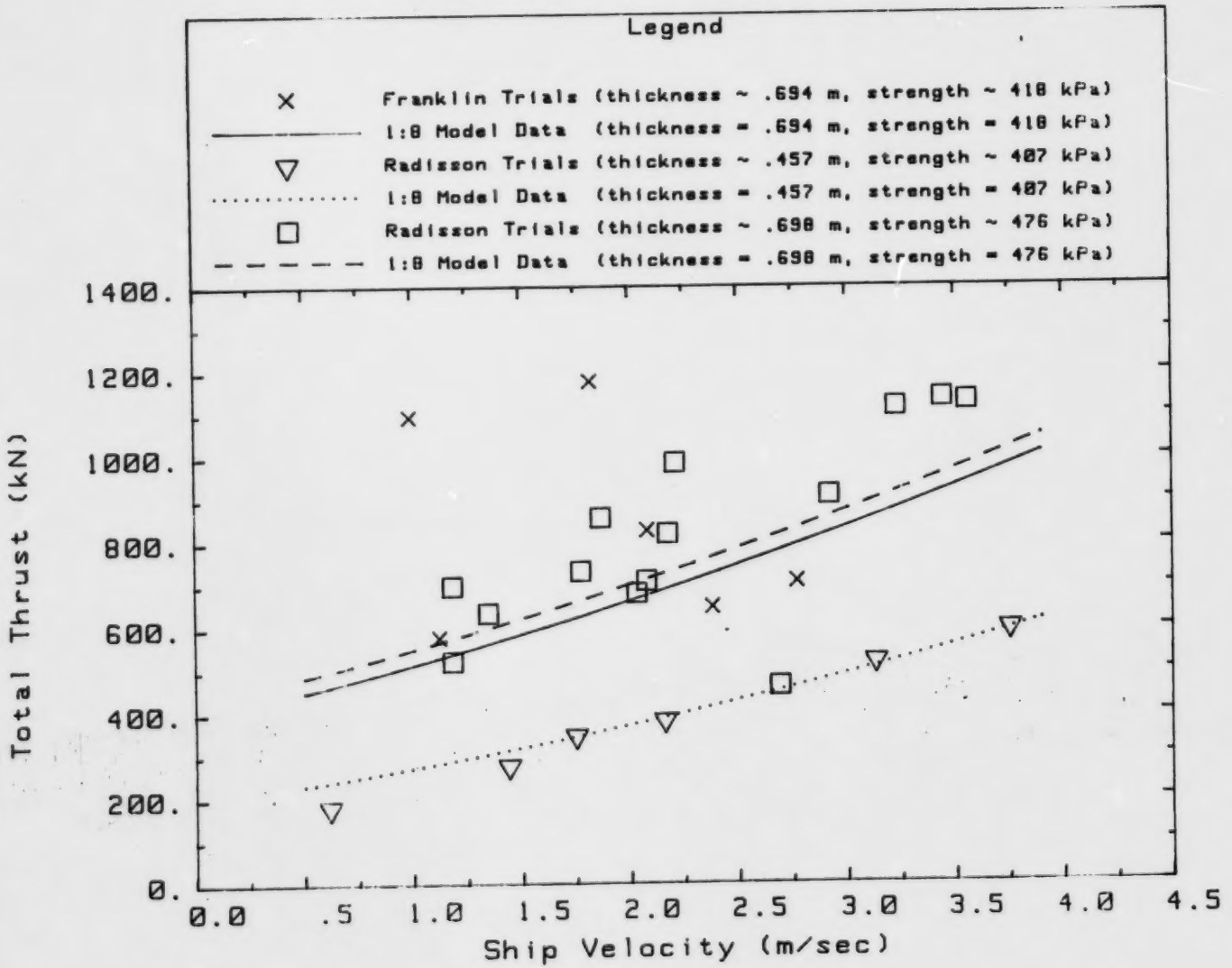
5.2 Comparison with Model Scale Data

It is not within the scope of work of this project to do a detailed comparison with the vast amount of model R-Class data. However, the primary objective of this project is to determine if scale effects exist in model ice resistance testing. Therefore, a comparison with some data is necessary.

The conditions tested within the vast amount of R-Class data vary widely. Some data is at different displacements. Other data is at different friction factors. Some data, although at the same displacement and friction, vas only ballasted statically: no consideration vas given to the position of the centre of gravity or the roll and pitch radii of gyration. To be able to compare with other data bases, either these parameters must be constant, or a reasonable correction must be known.

FIGURE 5.1

Full Scale vs Model Scale Comparison of the Data



Without doing a detailed search of the test conditions of each data base, one set of data which is known to be similar, is reported in [8]. This data was collected using the 1:20 fibreglass R-Class model. These tests were performed at a full scale draft of 7.16 m (on an even keel). The longitudinal radius of gyration was approximately 0.25 L_{OA}, and the full scale roll period was about 8.3 seconds. During these tests, the hull friction factor was approximately 0.05. This compares with the conditions for this test program of a mean full scale draft of 7.01m (6.77m forward and 7.22m aft). The longitudinal radius of gyration was approximately 0.25 L, the full scale roll period was about 11.6 seconds, and a hull friction of about 0.11 to 0.13. Although not identical, these conditions are similar.

The 1:20 scale total resistance equation is (reproduced from equation 6.9 of [ ]):

$$(R_T)_{M.S.} = -7.634 + 4014.9\, h^{1.5} + 2602.98\, vh + 9.31 \sigma h \qquad (5.8)$$

Using Froude scaling to convert into full scale units:

$$(R_T)F.S. = -61.1 + 359.1\, H^{1.5} + 232.8\, VH + 0.1862\, \sigma_f\, H \qquad (5.9)$$

$(R_T)_{F.S.}$ = full scale total resistance (in kN)

$(R_T)_{M.S.}$ = model scale total resistance (in m)

H = full scale ice thickness (in m)

h = model scale ice thickness (in m)

V = full scale velocity (in m/sec)

v = model scale velocity (in m/sec)

$(\sigma_f)_{F.S.}$ = full scale flexural strength (in kPa)

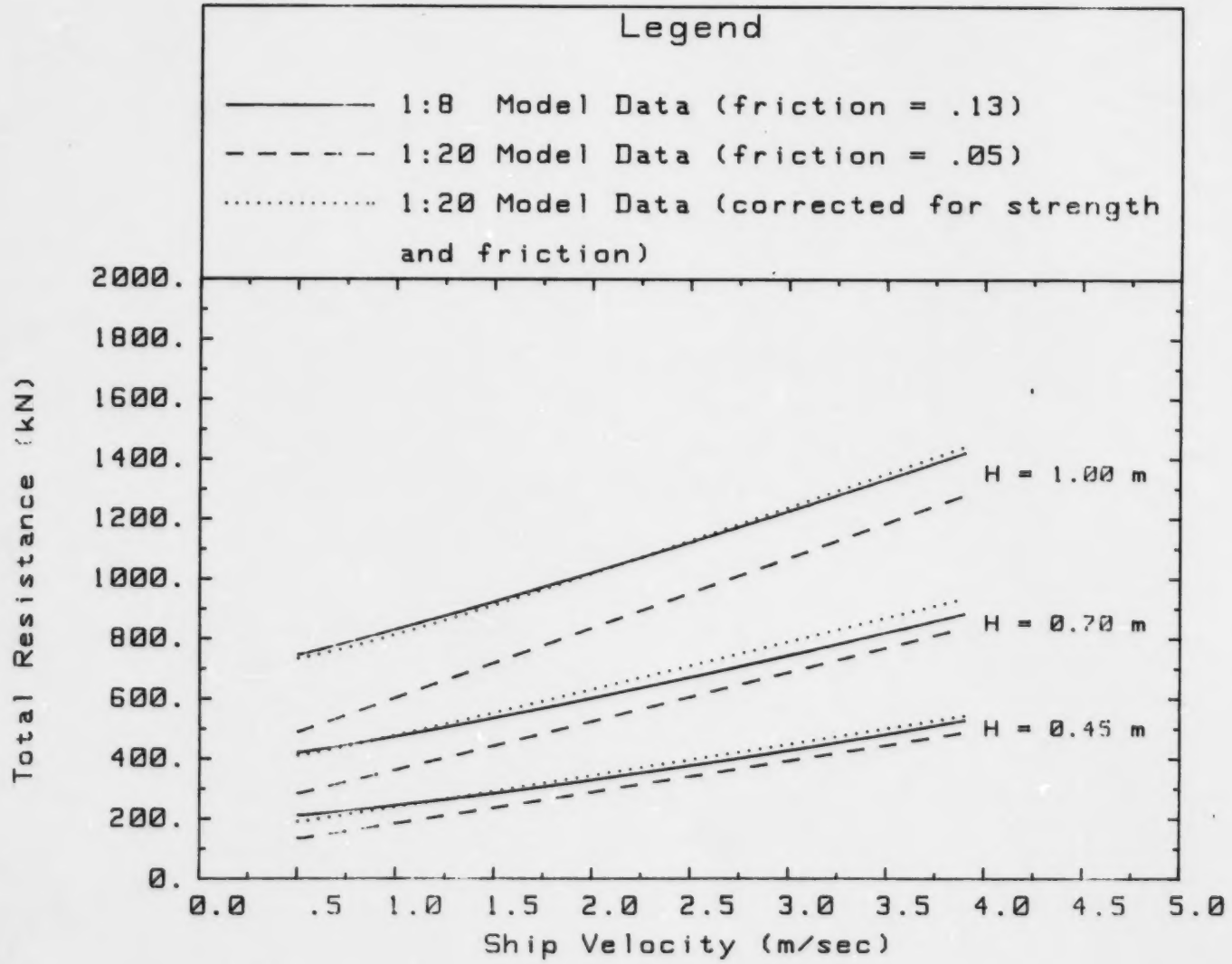
$(\sigma_f)_{M.S.}$ = model scale flexural strength (in kPa)

Also given in equation 6.19 of [8], is a nondimensional resistance equation for the R-Class which includes hull friction. Although most nondimensional predictor equations have more scatter than dimensional equations, this equation can be used to normalize equation 5.9 for hull friction.

Figure 5.2 and 5.3 shows equation 5.5 (for the 1:8 scale model) plotted against equation 5.9 (for the 1:20 scale model) at the target ice thicknesses and strengths. An additional line is also included to correct equation 5.9 for the hull friction (as done in [8]), and flexural strength (as done in Section 4.5).

FIGURE 5.2

Comparison of the Model Scale Results at a strength of 400 kPa



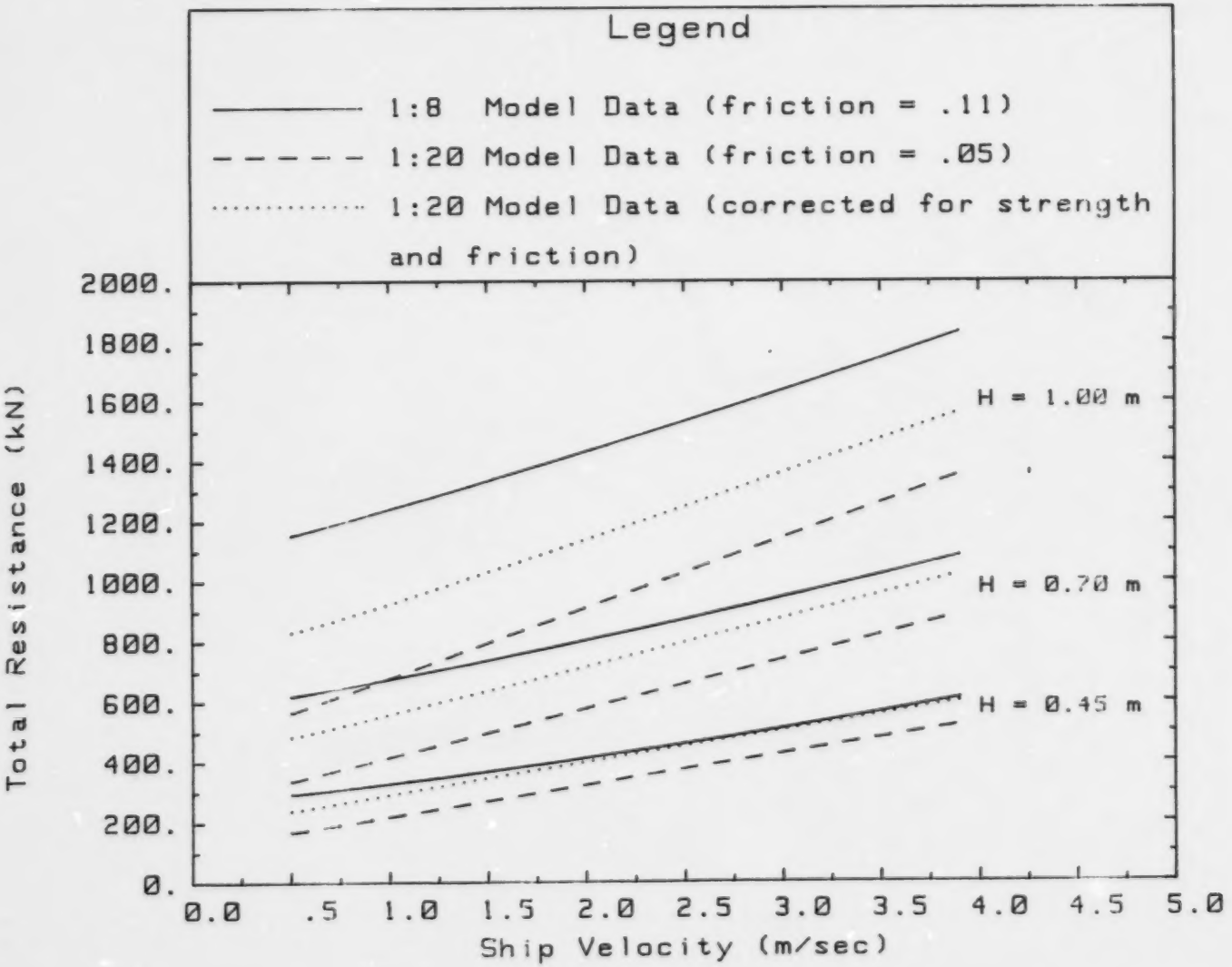
At a full scale flexural strength of 400 kPa, the corrected 1:20 equation fits quite well to the 1:8 equation. However, there is a slight thickness discrepancy. At a thickness of 1.0 m and a strength of 400 kPa, the corrected 1:20 equation is 1.7% below and 1.5% above the 1:8 equation for speeds of 0.5 and 4.0 m/sec respectively. At a thickness of 0.70 m, the corrected 1:20 equation is 2.5% below and 5.7% above the 1:8 equation. At a thickness of 0.45 m, the corrected 1:20 equation is 10.6% below and 2.5% above the 1:8 equation. Thus the velocity slope and the thickness slope and power are slightly different between the two model scales.

However, at a full scale flexural strength of 800 kPa, even the corrected 1:20 equation fits poorly. Thus the strength term in the two sets of data does not agree. Possible causes for this disagreement could be differences in the strength measurement techniques which are not already accounted for. Differences in the flexural failure mechanism between the two ice modelling materials (the 1:8 tests used EG/AD ice whereas the 1:20 tests used saline ice) may have also caused this discrepancy. The hull friction correction used may not have the correct strength dependency.

Therefore the conclusion that can be drawn from these tests is that the two model scales appear to agree quite well for some conditions and quite poorly at other conditions. Before it is possible to determine if a scale effect exists in model ice resistance testing, two (or more) completely identical test matrices must be performed at two (or more) different scale factors. It is essential that the hull friction factors be matched, that the ballast conditions be the same (both draft and trim), and that the roll and pitch period be the same.

FIGURE 5.3

Comparison of the Model Scale Results
at a strength of 800 kPa



6. CONCLUSIONS

The agreement between the 1:8 scale model results reported herein and the available full scale data is excellent, although only a limited amount of R-Class data without a snow cover is available at present.

The R-Class data base at model scale is, however, inconsistent and prevents drawing any firm conclusions. The 1:20 model data given in [8], after various corrections, appears to agree quite well for some ice conditions, yet quite poorly in others. It is not known whether this is a scale effect or an error in the correction method. Regardless, the 1:20 and 1:40 R-Class models must be retested at precisely the same test conditions as are reported herein, before the scale effect question can be answered.

The open water resistance term (or velocity power term) observed in the level ice resistance equation appears to be 37.4% larger than that measured in ice free water. This fact on its own does not verify the hypothesis that the open water resistance term in level ice is not the same as the open water resistance measured in clear water. However, it does raise questions regarding the validity of simply subtracting the open water resistance from the total resistance in ice, to give the icebreaking resistance.

The broken floes observed in the EG/AD ice, even at a scale of 1:8, were too large. Although the EG/AD ice was initially cracking in a manner which may have produced a smaller piece size distribution, the residual strength of this ice was high and as a result, these initial flexural cracks did not propagate through the ice thickness. Even after passing under the hull, the floes were still too large for current geometric scaling of piece size.

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APPENDIX I

IMD'S REPORT

National Research Council Canada
Conseil national de recherches Canada

Institute for Marine Dynamics
Institut de dynamique marine

Test Report TR-AVR-07

TESTS IN ICE OF A 1:8 SCALE MODEL OF THE CCG R-CLASS HULL

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Canada

TESTS IN ICE OF A 1:8 SCALE MODEL OF THE CCG R-CLASS HULL

TR-AVR-07

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SUMMARY

A series of model tests was carried out on a 1:8 scale model of the CCG R-Class hull. The range of model velocities and ice parameters covered those suggested by the ITTC. The purpose of the tests was to provide relatively large scale ice resistance data for comparison with model tests on the same hull at 1:20 and 1:40 scale.

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TR-AVR-07

TESTS IN ICE OF A 1:8 SCALE MODEL OF THE CCG R-CLASS HULL

1.0 INTRODUCTION

This report presents the results of a series of model tests in ice performed on a 1:8 scale model of the CCG R-Class hull. These tests were performed as part of an ongoing effort to verify scaling methods and ship-ice testing procedures using the R-Class hull. At the present time, work on 1:20 scale and 1:40 scale R-Class testing is continuing.

This test series was conducted in cooperation with Arctec Canada Inc. on behalf of Transport Canada Transport Development Centre.

2.0 MODEL

The 1:8 scale R-Class model, designated Model M 389 was milled to the R-Class lines shown in Figure 1. These are the same lines used to generate the 1:20 and 1:40 scale hull forms. The model consists of a wooden inner hull covered with polyurethane foam over coated with glass reinforced polyester resin. The moulded lines were cut in the foam layer followed by application of the fibreglass. This outside skin has a mean thickness of approximately 8 mm. Final surface coating was with a two component epoxy paint mixed with flattening agent to give the desired surface roughness. The model was not fitted with any appendages.

Test conditions for the model were as follows:

Forward Draft	846 mm (838 moulded)
Aft Draft	902 mm (894 moulded)
Mean Draft	876 mm (868 moulded)
Moulded Displacement (FW)	14,905 kg
Actual Displacement (Approx)(FW)	15,245 kg
KB	485 mm
KM	1096 mm
KG	969 mm
Roll Period	4.1 sec
Length BP	10.992 m
Length WL	11.625 m
Midship Beam (Max)	2.420 m
LCB Fwd of Midship	40 mm

3.0 EXPERIMENTAL PROCEDURE

The model was towed on a rigid towing system in the IMD refrigerated towing basin. This towing system allows model freedom in heave, pitch and roll and provides restraint in surge sway and yaw. For each test the following parameters were measured:

1	Model Speed	m/sec
2	Tow Force	N
3	Roll	deg.
4	Pitch	deg.
5	Heave	mm
6	Side Force at Yaw Restraint	N

In general, three speeds were run in each sheet of ice resulting in run length of approximately 20 m. This is slightly shorter than 2 ship lengths. A number of longer runs were done to confirm that the resistance reached steady state within this length. The measurement interval was taken as the last 8 m in each 20 m run.

Target ice properties were 56 mm 50 kPa, 56 mm 100 kPa, 88 mm 50 kPa, 88 mm 100 kPa and 125 mm 100 kPa. Three model speeds (.24 m/s, .48 m/s and .95 m/s) were run in each of these ice conditions with some repeat runs performed. In addition, presawn tests were performed for 56 mm and 88 mm ice at each of the three model speeds.

Ice strength was measured using cantilever beam tests at locations on either side of the model track in the middle area of the tank. Ice thickness was measured following each test at 2 m intervals on both sides of the model track. These results were averaged over the measurement intervals to give an icethickness for each run.

Periodically, ice friction measurements were carried out on a sample with a surface coating prepared at the same time and in the same way as the model surface.

The model tow point was located at the centre of gravity and the yaw restraint was located at a centre approximately 3088 mm aft of the tow post centre. Thus measured yaw loads should be multiplied by 3.088 to give yaw moments.

As part of the test program the broken piece size was photographed in the channel aft of the vessel. Piece size averages are given in the results section following. It is intended that a more in depth analysis of this data be performed at a later date.

4.0 RESULTS

Results of the trials are given in Table 1 including ice properties and mean or RMS values of all recorded parameters. Tests showing zero ice strength are presawn ice sheets. In addition, open water runs were performed for the three test speeds with recorded results given in Table 2. Ice friction values are presented in Table 3. More detailed ice properties for each of the test sheets appear in the following section.

In general the quality of the recorded data is judged to be very good although there is considerable scatter around the target ice strength and thickness. This is particularly true of ice strength, however at the target values of 100 and 50 kPa there was some difficulty in predicting tempering time and in measuring the ice strength. These strengths are substantially higher than those normally used in model ice tests.

A measuring equipment problem resulted in the loss of some data in the 125 mm 100 kPa ice test. Thus the resistance value indicated for .95 m/s @ 111 kPa and 129.4mm is an estimate based on graphical reconstruction of the recoverable information in the resistance time series. The presawn results appear to show a slight strength effect in that the presawn tests conducted at .95 m/s were done in relatively low strength ice and these resistance results seem to be low when compared to tests conducted at lower speeds. This strength effect appears to manifest itself in local crushing between the sawn ice floes and the model. Alternately the strength of the ice may influence the degree of secondary breaking. For the purposes of these tests the presawn results were used to provide a means of correcting the data to target strength and thickness. Thus slight errors in these results are not judged to have a major effect on the overall ice resistance prediction.

In order to provide results at the desired strength and thickness of ice, a correction method was applied to the gathered data. The basic steps in this method are as follows:

a) The presawn resistances are plotted against test ice thickness and a fair curve drawn through the data for each speed. These curves are used to supply presawn resistances at thicknesses corresponding to each level ice test run and a presawn resistance at each target thickness. No attempt was made to separate the open water resistance because it is not clear how the ice sheet influences the hydrodynamic resistance of the model.

b) For each level ice run, the relevant presawn resistance is subtracted to yield a residual resistance for the given ice strength and thickness.

c) A linear correction for ice strength is applied to each residual resistance based on the percentage deviation from the target ice strength.

d) The resulting residual (or breaking) resistance values are plotted against ice thickness for each speed and target ice strength value. A fair curve is drawn through each set of points. These curves are used to determine a breaking resistance at the target thickness, strength, and speed.

e) The corrected breaking resistance values are added to the corrected presawn resistance values to yield a total icebreaking resistance for the target strength and thickness values. These results are given in Table 4 and shown in Figure 2.

Functionally this can be expressed as:

R_p - measured pre-sawn resistance
R_T - measured level ice resistance

a) $R_p = f(h)$

b) $R_B(h_o, \sigma_o) = R_T(h_o, \sigma_o) - f(h_o)$

c) $R_B(h_o, \sigma_t) = R_B(h_o, \sigma_o)\left(1 + \frac{\sigma_t - \sigma_o}{\sigma_o}\right)$

d) $R_B(h, \sigma_t) = g(h, \sigma = \text{const. } \sigma_t)$

e) $R_T(h_t, \sigma_t) = f(h_t) + g(h_t, \sigma_t)$

where R_B - breaking resistance
h - ice thickness
σ - ice strength
o - measured value
t - target value
f - arbitrary function
g - arbitrary function

Model motions, (roll, pitch and heave) were recorded at the towing gimbal referenced to the model centre of gravity. The predominant motion in an icebreaking situation is vertical motion at the bow which results in both heave and pitch in the model. However these motions are quasi-static in nature and thus the pitch centre is probably the centre of flotation which is some distance aft of the model c.g. This would result in a larger apparent heave and a smaller apparent pitch at the model c.g. Thus in the recorded results, the heave is the best indicator of the relative motion at the model bow.

TABLE 1 1:8 R-CLASS TEST RESULTS, TEST DATA

Ice Sheet No.	Model Speed (m/s)	Ice Strength (kPa)	Ice Thickness (mm)	Mean Resistance (N)	Yaw Load (N rms)	RMS Roll Amplitude (deg)	Pitch Amplitude (deg)		Heave Amplitude (mm)	
							Steady	RMS	Steady	RMS
1	.48	0	55.1	404	507	0.1	0.1	0.1	2.1	2.4
1	.48	95	54.4	610	1046	0.2	0.1	0.1	1.9	2.2
1	.48	95	53.4	567	1241	0.1	0.1	0.1	1.7	1.9
2	.95	98	55.5	931	1908	0.2	0.2	0.0	0.1	1.3
2	.24	98	54.4	566	792	0.3	0.1	0.1	3.0	3.2
2	.24	63	56.3	471	600	0.3	0.1	0.1	2.9	1.8
3	.24	116	90.5	1380	1726	0.7	0.3	0.1	12.0	4.9
3	.48	116	90.6	1690	1654	0.6	0.4	0.1	11.0	2.8
3	.48	0	88.0	766	569	0.2	0.1	0.1	3.5	2.2
4	.95	90	88.6	1643	3053	0.3	0.4	0.1	6.3	4.3
4	.24	0	89.2	487	206	0.1	0.1	0.0	2.3	0.9
4	.24	48	88.7	813	864	0.5	0.2	0.1	6.0	2.3
5	.48	48	90.4	1098	1930	0.4	0.2	0.1	8.5	3.5
5	.95	48	88.3	1453	2979	0.3	0.2	0.0	1.1	4.6
5	.95	0	87.9	851	318	0.2	0.1	0.0	-.2	1.5
6	.48	56	57.4	587	1017	0.1	0.2	0.0	3.4	2.9
6	.95	56	58.0	842	1346	0.2	0.1	0.0	-3.5	2.6
6	.95	0	55.2	472	155	0.1	0.1	0.0	-5.0	2.4
7	.24	111	134.1	2850	2718	0.9	0.8	0.2	23.4	4.9
7	.48	111	134.6	3100	2834	0.8	0.9	0.3	23.3	6.5
7	.95	111	129.4	3400	3413	0.4	0.8	0.1	19.7	5.2
8	.95	90	55.9	990	1913	0.3	0.1	0.0	-.6	2.9
8	.24	0	54.0	193	130	0.1	0.0	0.0	0.8	1.0
9	.24	90	90.1	1149	1478	0.6	0.4	0.1	9.9	2.7
9	.95	90	88.8	1810	3046	0.6	0.4	0.1	6.1	4.2
10	.70	91	47.0	643	777	0.1	0.1	0.0	1.9	2.4
10	.95	91	47.3	721	1437	0.2	0.1	0.0	-4.2	2.2
10	.24	91	44.4	446	576	0.2	0.1	0.0	2.1	3.4

TABLE 2 1:8 R-CLASS TEST RESULTS

OPEN WATER RESISTANCE

Model Speed (m/s)	Mean Resistance (N)	Yaw Load (N)	RMS Roll Amplitude (deg)	RMS Pitch Amplitude (deg)	RMS Heave Amplitude (mm)	
.24	15	24	---	---	---	---
.48	45	24	0.0	0.0	-.80	2.0
.95	135	26	0.0	0.0	-4.3	2.4

TABLE 3 1:8 R-CLASS TEST RESULTS

FRICTION COEFFICIENTS

Ice sample dimensions 150 x 150 mm nominal

Ice Strength (kPa)	Condition (wet/dry)	Surface	Normal Force (N)	Tangential Force (N)	Friction Coefficient
50	Dry	Top	19.6	1.1	.05
50	"	"	49.1	5.2	.11
50	"	"	98.1	12.9	.13
50	"	"	147.2	19.8	.13
50	"	"	196.2	24.9	.13
50	Wet	Top	19.6	0.9	.04
50	"	"	49.1	4.3	.09
50	"	"	98.1	12.0	.12
50	"	"	147.2	18.9	.13
50	"	"	196.2	25.8	.13
56	Dry	Top	19.6	1.6	.08
56	"	"	49.1	4.5	.09
56	"	"	98.1	11.1	.11
56	"	"	147.2	17.2	.12
56	"	"	196.2	24.6	.13
56	Wet	Top	19.6	1.2	.06
56	"	"	49.1	4.9	.10
56	"	"	98.1	10.7	.11
56	"	"	147.2	16.4	.11
56	"	"	196.2	23.0	.12

TABLE 3 (CONTINUED)

Ice Strength (kPa)	Condition (wet/dry)	Surface	Normal Force (N)	Tangential Force (N)	Friction Coefficient
90	Dry	Top	19.6	6.5	.33
90	"	"	49.1	10.5	.21
90	"	"	98.1	16.2	.17
90	"	"	147.2	21.9	.15
90	"	"	196.2	27.5	.14
90	Wet	Top	19.6	4.9	.25
90	"	"	49.1	8.5	.17
90	"	"	98.1	14.6	.15
90	"	"	147.2	20.3	.14
90	"	"	196.2	26.7	.14
90	Wet	Top	19.6	0.9	.05
90	"	"	49.1	3.4	.07
90	"	"	98.1	9.4	.10
90	"	"	147.2	15.0	.10
90	"	"	196.2	20.6	.11
111	Wet	Top	19.6	3.0	.15
111	"	"	49.1	6.4	.13
111	"	"	98.1	12.8	.13
111	"	"	147.2	17.3	.12
111	"	"	196.2	21.8	.11
111	Wet	Side	19.6	4.9	.25
111	"	"	49.1	6.0	.12
111	"	"	98.1	11.3	.11
111	"	"	147.2	17.6	.12
111	"	"	196.2	23.3	.12

TABLE 4 1:8 R-CLASS TEST RESULTS

CORRECTED ICE RESISTANCE

Model Speed (m/s)	Ice Thickness (mm)	Ice Strength (kPa)	Presawn Resistance (N)	Breaking Resistance (N)	Total Resistance (N)
.24	56	50	210	202	412
.48	56	50	415	135	550
.95	56	50	488	290	778
.24	56	100	210	390	600
.48	56	100	415	230	645
.95	56	100	488	470	958
.24	88	50	480	340	820
.48	88	50	760	300	1060
.95	88	50	850	620	1470
.24	88	100	480	710	1190
.48	88	100	760	675	1435
.95	88	100	850	980	1830
.24	125	100	907*	1420	2327
.48	125	100	1245*	1350	2595
.95	125	100	1330*	1750*	3080

* Based on Extrapolated Data

TABLE 5 1:8 R-CLASS TEST RESULTS

PIECE SIZE DISTRIBUTION

Test	Ice Thickness	Ice Strength	Model Speed	Av. Piece Length (m) ±SD	Av. Piece Area (m^2) ±SD
8R1	53.9	95	.48	.410 ± .368	.065 ± .106
8R2	55.5	98	.95	.384 ± .282	.060 ± .079
	54.4	98	.24	.306 ± .214	.037 ± .039
	56.3	63	.24	.287 ± .178	.036 ± .039
8R3	90.5	116	.24	.339 ± .272	.052 ± .072
	90.6	116	.48	.274 ± .200	.036 ± .039
8R4	88.6	90	.95	.384 ± .249	.066 ± .072
8R5	90.4	48	.48	.435 ± .285	.075 ± .070
	88.3	48	.95	.484 ± .307	.093 ± .102
8R8	134.1	111	.24	.480 ± .397	.110 ± .175
	134.6	111	.48	.406 ± .307	.076 ± .087
	129.4	111	.95	.404 ± .301	.102 ± .097
8R9	55.9	90	.95	.404 ± .201	.055 ± .050

Within the intervals selected for measurement, roll motions were consistently very low. However the model was observed to exhibit significant roll motions during transitional periods of the test (ie when first entering the ice sheet of shortly after changes in speed).

The data on piece size is presented in tabular form as averages and standard deviations for the tests during which this data was recorded.

Measured yaw loads were recorded at the yaw restraint only. This measurement was somewhat experimental in that this test series was the first time the yaw force was recorded at IMD. This measurement by itself does not give complete information on sideloads on the model but can be used to estimate side forces at the bow. In general the RMS value of the yaw load was on the order of one to two times the mean resistance of the model. This translates into average side loads at the bow of 50 to 100% of the average resistance.

5.0 PROPERTIES

Average ice properties are presented for each of the test ice sheets. In those cases where two sets of properties are shown for a single sheet, one portion of the sheet was used at the first strength and the remainder of the sheet used after tempering to the lower strength. With the exception of strength, all parameters were recorded either shortly before or shortly after the test. Strength has been interpolated to give a value at test time. In this and all cases in the report, strength is defined as Flexural Strength as measured by cantilever beam test.

TABLE 6 ICE PROPERTIES

Ice Sheet	Test	Average Thickness (mm)	Average Strength (kPa)	E/σ	Fracture Toughness kPa/$\sqrt{m}$	Comp. Strength (kPa)	Density Mg/m^3
1	8R1	55.0	95	2840	NR	178	.928
2	8R2a	54.9	98	3570	NR	152	.927
	8R2b	56.2	63	3050	NR	168	NR
3	8R3	91.2	116	6640	NR	NR	.923
4	8R4a	87.6	90	2910	20.7	NR	.923
	8R4b	88.8	48	3110	7.1	NR	.927
5	8R5	88.7	48	3110	10.4	138	.928
6	8R7	57.1	56	1770	NR	NR	.931
7	8R8	133.1	111	3860	37.8	NR	NR
8	8R9	55.7	90	1960	NR	220	.924
9	8R10	88.7	90	3160	NR	178	.924
10	8R11	46.0	91	1910	17.1	172	.928

6.0 DISCUSSION AND CONCLUSION

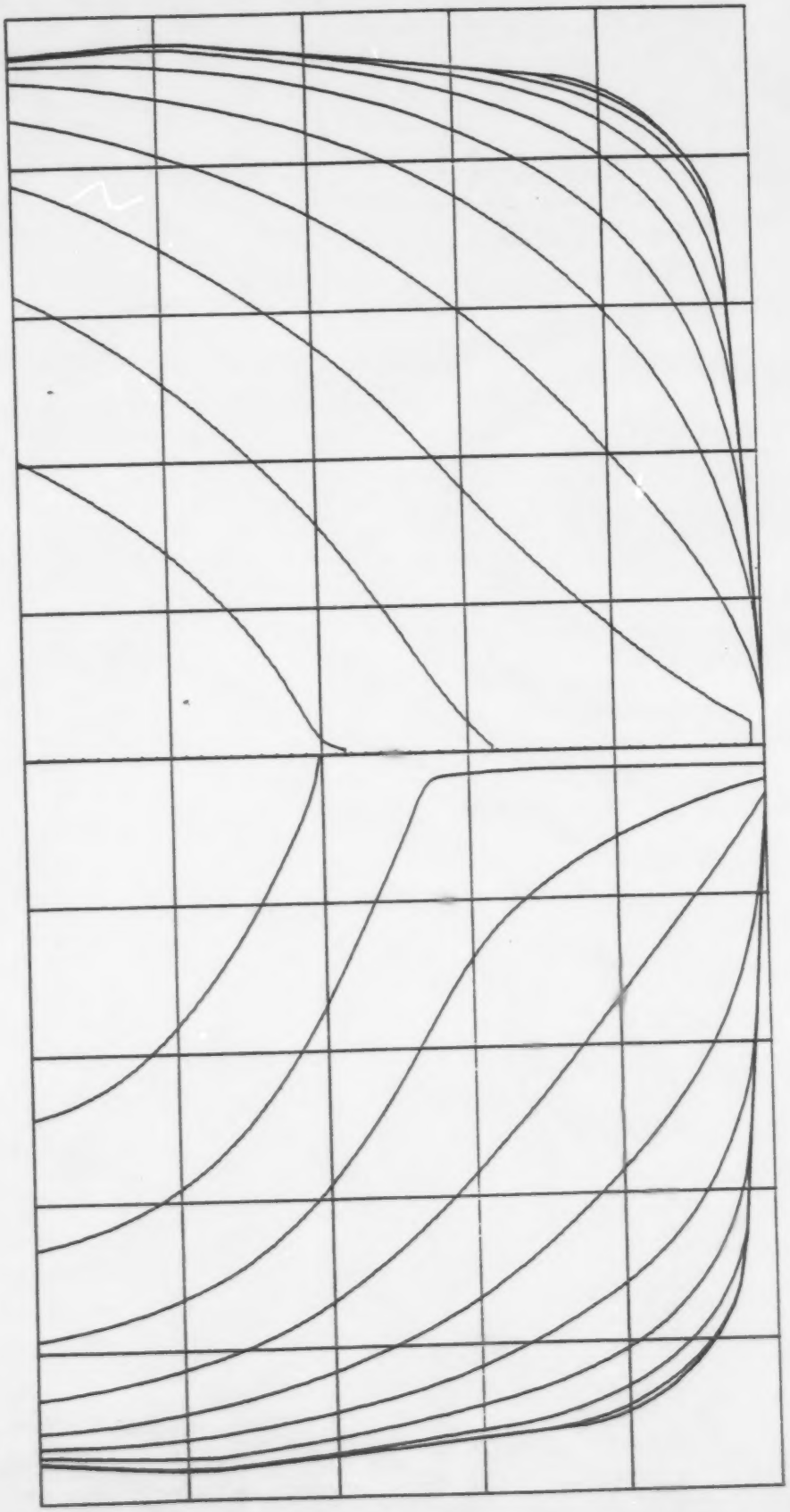
The data gathered during this test series showed features not easily discernable in smaller scale tests. The most important of these is the effect of ice strength. Although only two strengths were tested, the trend of increasing resistance with increasing flexural strength is clearly demonstrated, both in the raw data and in the final predictions.

Vessel motions also appear to play some part in ice resistance. As model speeds increase, the oscillating vertical motion in the bow tends to decrease. The pattern of the model bow riding up onto the ice sheet and then breaking the ice is only evident at lower speeds. At higher speeds, icebreaking becomes more of a continuous process with reduced bow motions as the ice is pushed more smoothly under the model. This difference in motions may indicate two modes of icebreaking related to model speed and overall ice strength. The low speed mode would consist of the model riding up on the ice and forcing it down in discrete steps with the accompanying higher vertical oscillation at the bow. The higher speed mode on the other hand would not involve appreciable oscillation of the bow with the ice being forced down and broken at a faster rate than the model is able to react.

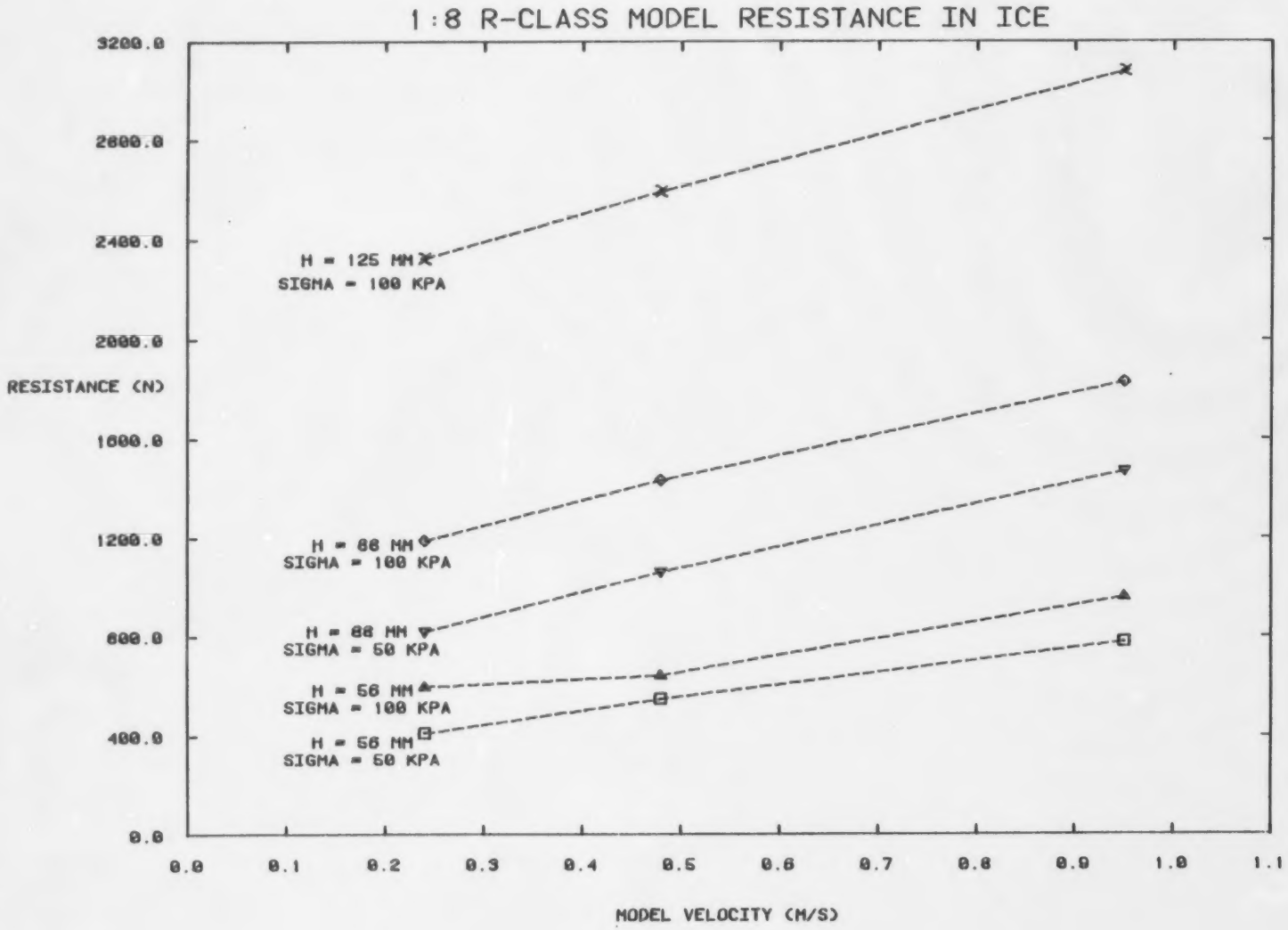
Other than these two features, the recorded resistances appear to be in keeping with both smaller scale results and available full scale data. As the remaining R-Class data is gathered it is expected that differences in prediction at various scales will be explored and discussed in more detail.

In conclusion although testing a 1:8 scale model presents a number of practical problems related to model size and ice strength, the results are judged to be worth the effort. Studies of this type add considerably to the reliability of ice-model testing by enlarging the data base and providing data for the development of improved scaling methods.

Figure 1



R-Class Lines



TR-AVR-07

Figure 2

APPENDIX II

LEVEL ICEBREAKING STATISTICAL OUTPUT

****

STEPWISE REGRESSION ON
1:8 R-Class Level Icebreaking

****

Dependent variable:R (N)
Independent variable(s) = v (m/s)
Sig (kPa)
h (m)
h^1.5
h^2
vh
vh^1.5
vh^2
Sig h
Sig h^2
Sig v
v^2
v^3
v^1.597

Tolerance = .01
F-value for inclusion = 4
F-value for deletion = 4

CORRELATION MATRIX

	v (m/s)	Sig (kPa)	h (m)	h^1.5	h^2	vh
v (m/s)	1.0000000	.0033479	-.0596042	-.0621452	-.0640106	.8039180
Sig (kPa)		1.0000000	.2092032	.2379181	.2637959	.0996884
h (m)			1.0000000	.9967320	.9871438	.4775225
h^1.5				1.0000000	.9968236	.4720906
h^2					1.0000000	.4636722
vh						1.0000000

	vh^1.5	vh^2	Sig h	Sig h^2	Sig v	v^2
v (m/s)	.6563616	.5332923	-.0374523	-.0541628	.6287052	.9899813
Sig (kPa)	.1459212	.1844825	.8268007	.6351322	.6888300	.0030256
h (m)	.6271979	.7108171	.6893605	.8266962	.0900967	-.0518801
h^1.5	.6254307	.7140377	.7163205	.8568582	.1089954	-.0553026
h^2	.6195252	.7124100	.7379919	.8810934	.1263666	-.0581345
vh	.9749762	.9256790	.3223830	.3815493	.5844518	.8000689
vh^1.5	1.0000000	.9862990	.4425441	.5254661	.5312916	.6542990
vh^2		1.0000000	.5229088	.6208943	.4874447	.5320686
Sig h			1.0000000	.9553235	.5328828	-.0337430
Sig h^2				1.0000000	.3881046	-.0504573
Sig v					1.0000000	.6206097
v^2						1.0000000

	v^3	v^1.597	R (N)
v (m/s)	.9725869	.9958930	.1842377
Sig (kPa)	.0014445	.0033565	.5308476
h (m)	-.0438466	-.0551632	.8734457
h^1.5	-.0480111	-.0582439	.8943712
h^2	-.0516367	-.0607037	.9092017
vh	.7903825	.8030660	.6278431
vh^1.5	.6476438	.6562719	.7452962
vh^2	.5273543	.5334469	.8119232
Sig h	-.0304617	-.0352356	.8865273
Sig h^2	-.0464293	-.0520751	.9525624
Sig v	.6073872	.6251463	.4815528
v^2	.9956354	.9986967	.1844799
v^3	1.0000000	.9895939	.1840974
v^1.597		1.0000000	.1845905
R (N)			1.0000000

#--VARIABLE	F TO ENTER	PART CORR	TOL	F TO DELETE	REGRESSION COEFFICIENTS STD.FORMAT	E-FORMAT	STD ERROR
2.v (m/s)	.91	.184	1.000				
3.Sig (kPa)	10.20	.531	1.000				
4.h (m)	83.66	.873	1.000				
6.h^1.5	103.93	.894	1.000				
7.h^2	123.98	.909	1.000				
8.vh	16.92	.628	1.000				
9.vh^1.5	32.49	.745	1.000				
10.vh^2	50.30	.812	1.000				
11.Sig h	95.46	.887	1.000				
12.Sig h^2	254.70	.953	1.000				
13.Sig v	7.85	.482	1.000				
14.v^2	.92	.184	1.000				
15.v^3	.91	.184	1.000				
16.v^1.597	.92	.185	1.000				

STEP NUMBER 1
VARIABLE'Sig h^2 ' ADDED
R-SQUARED = .907375140721

AOV

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE
TOTAL	27	1.8393061E+07		
REGRESSION	1	1.6689407E+07	6.4190025E+05	254.70
RESIDUAL	26	1703654.70999	65525.18115	

STANDARD ERROR = 255.978868568

#--VARIABLE	F TO ENTER	PART CORR	TOL	F TO DELETE	REGRESSION COEFFICIENTS STD.FORMAT	E-FORMAT	STD ERROR
2.v (m/s)	37.85	.776	.997				
3.Sig (kPa)	2.76	.315	.597				
4.h (m)	8.42	.502	.317				
6.h^1.5	8.25	.498	.266				
7.h^2	7.72	.486	.224				
8.vh	189.20	.940	.854				
9.vh^1.5	209.64	.945	.724				
10.vh^2	146.34	.924	.614				
11.Sig h	1.83	.261	.087				
12.Sig h^2				254.70	1343.20295	.134320295098E+04	84.1638
13.Sig v	4.73	.399	.849				
14.v^2	35.29	.765	.997				
15.v^3	32.35	.751	.998				
16.v^1.597	36.54	.771	.997				

Constant = 450.386180425

```
**********
STEP NUMBER 2
VARIABLE'vh^1.5     ' ADDED
R-SQUARED =  .990131333908

                                AOV

SOURCE              DF      SUM OF SQUARES        MEAN SQUARE         F-VALUE
TOTAL               27      1.8393061E+07
REGRESSION           2      1.8211546E+07       728461.85080          1254.14
RESIDUAL            25       181514.97989         7260.59920

STANDARD ERROR =  85.2091497187

                  F TO  PART          F TO       REGRESSION COEFFICIENTS        STD
#--VARIABLE      ENTER  CORR   TOL DELETE  STD.FORMAT              E-FORMAT     ERROR
 2.v (m/s)         .13  .073  .349
 3.Sig (kPa)       .51  .145  .548
 4.h (m)          4.74  .406  .265
 6.h^1.5          4.66  .403  .223
 7.h^2            4.36  .392  .190
 8.vh              .62  .158  .026
 9.vh^1.5                       209.64  29187.84789  .291878478858E+05 2.02E+03
10.vh^2           1.47  .240  .013
11.Sig h           .34  .118  .082
12.Sig h^2                     1.E+03   1092.67384  .109267383624E+04  32.9285
13.Sig v          0.00  .014  .701
14.v^2             .04  .040  .357
15.v^3             .01  .018  .374
16.v^1.597         .06  .052  .352

Constant =  209.864819395

**********
STEP NUMBER 3
VARIABLE'h (m)      ' ADDED
R-SQUARED =  .991759145887

                                AOV

SOURCE              DF      SUM OF SQUARES        MEAN SQUARE         F-VALUE
TOTAL               27      1.8393061E+07
REGRESSION           3      1.8241487E+07       760061.94648           962.77
RESIDUAL            24       151574.53446         6315.60560

STANDARD ERROR =  79.4707845846

                  F TO  PART          F TO       REGRESSION COEFFICIENTS        STD
#--VARIABLE      ENTER  CORR   TOL DELETE  STD.FORMAT              E-FORMAT     ERROR
 2.v (m/s)        7.00  .483  .203
 3.Sig (kPa)      1.07  .211  .281
 4.h (m)                        4.74   2442.09642  .244209641518E+04 1.12E+03
Variable'h^1.5     'does not exceed tolerance.
 7.h^2            0.00  .003  .012
 8.vh             7.11  .486  .018
 9.vh^1.5                       177.77  27386.64485  .273866448455E+05 2.05E+03
10.vh^2           6.29  .464  .011
11.Sig h           .54  .152  .056
12.Sig h^2                     479.28   1016.80922  .101680922271E+04  46.4458
13.Sig v          7.99  .508  .320
14.v^2            4.61  .409  .219
15.v^3            3.12  .346  .246
16.v^1.597        5.51  .439  .209

Constant =  83.6423233893
```

```
**********
STEP NUMBER 4
VARIABLE'Sig v      ' ADDED
R-SQUARED =  .993883626162

                                AOV

SOURCE              DF      SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL               27      1.8393061E+07
REGRESSION           4      1.8280562E+07       794807.06136         934.35
RESIDUAL            23       112498.83863         4891.25385

STANDARD ERROR =  69.9374996224

                F TO  PART        F TO       REGRESSION COEFFICIENTS        STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT     ERROR
 2.v (m/s)      3.10  .351  .169
 3.Sig (kPa)    1.21  .228  .146
 4.h (m)                          14.10   5485.75289  .548575289447E+04 1.46E+03
Variable'h^1.5      'does not exceed tolerance.
 7.h^2          1.71  .269  .010
 8.vh           2.94  .343  .015
 9.vh^1.5                         69.39  21962.01806  .219620180576E+05 2.64E+03
Variable'vh^2       'does not exceed tolerance.
11.Sig h        1.87  .280  .032
12.Sig h^2                       253.06    904.97369  .904973687886E+03  56.8882
13.Sig v                           7.99      2.03493  .203493351542E+01    .7200
14.v^2          1.68  .266  .186
15.v^3           .95  .204  .214
16.v^1.597      2.17  .300  .176

Constant = -105.854864138

        Tolerance value too small and/or F-values insufficient to proceed.

**********
STEP NUMBER 5
VARIABLE'Sig v      ' DELETED
R-SQUARED =  .991759145887

                                AOV

SOURCE              DF      SUM OF SQUARES        MEAN SQUARE        F-VALUE
TOTAL               27      1.8393061E+07
REGRESSION           3      1.8241487E+07       760061.94648         962.77
RESIDUAL            24       151574.53446         6315.60560

STANDARD ERROR =  79.4707845846

                F TO  PART        F TO       REGRESSION COEFFICIENTS        STD
#--VARIABLE    ENTER  CORR   TOL DELETE  STD.FORMAT            E-FORMAT     ERROR
 2.v (m/s)      7.00  .483  .203
 3.Sig (kPa)    1.07  .211  .281
 4.h (m)                           4.74   2442.09642  .244209641518E+04 1.12E+03
Variable'h^1.5      'does not exceed tolerance.
 7.h^2          0.00  .003  .012
 8.vh           7.11  .486  .018
 9.vh^1.5                        177.77  27386.64485  .273866448455E+05 2.05E+03
10.vh^2         6.29  .464  .011
11.Sig h         .54  .152  .056
12.Sig h^2                       479.28   1016.80922  .101680922271E+04  46.4458
13.Sig v        7.99  .508  .320
14.v^2          4.61  .409  .219
15.v^3          3.12  .346  .246
16.v^1.597      5.51  .439  .209

Constant =  83.6423233893
```

```
**********************************************************************************
STEP NUMBER 6
VARIABLE'v^1.597    ' ADDED
R-SQUARED =  .993350919561


                                        AOV

SOURCE              DF      SUM OF SQUARES         MEAN SQUARE         F-VALUE
TOTAL               27       1.8393061E+07
REGRESSION           4       1.8270764E+07         794381.05679         859.03
RESIDUAL            23        122296.94377          5317.25842

STANDARD ERROR =  72.9195339032


                  F TO  PART         F TO        REGRESSION COEFFICIENTS        STD
#--VARIABLE     ENTER  CORR    TOL DELETE  STD.FORMAT             E-FORMAT     ERROR
Variable'v (m/s)'does not exceed tolerance.
 3.Sig (kPa)     .89  .197  .280
 4.h (m)                          11.05   4431.60546  .443160546245E+04 1.33E+03
Variable'h^1.5     'does not exceed tolerance.
 7.h^2           .02  .033  .012
Variable'vh        'does not exceed tolerance.
 9.vh^1.5                         20.94  18812.73763  .188127376254E+05 4.11E+03
Variable'vh^2      'does not exceed tolerance.
11.Sig h         .38  .130  .055
12.Sig h^2                       573.75   1022.40296  .102240295776E+04  42.6836
13.Sig v        4.28  .403  .269
Variable'v^2       'does not exceed tolerance.
15.v^3          2.11  .296  .020
16.v^1.597                         5.51    200.74238  .200742376719E+03  85.5491


Constant = -58.2246683134
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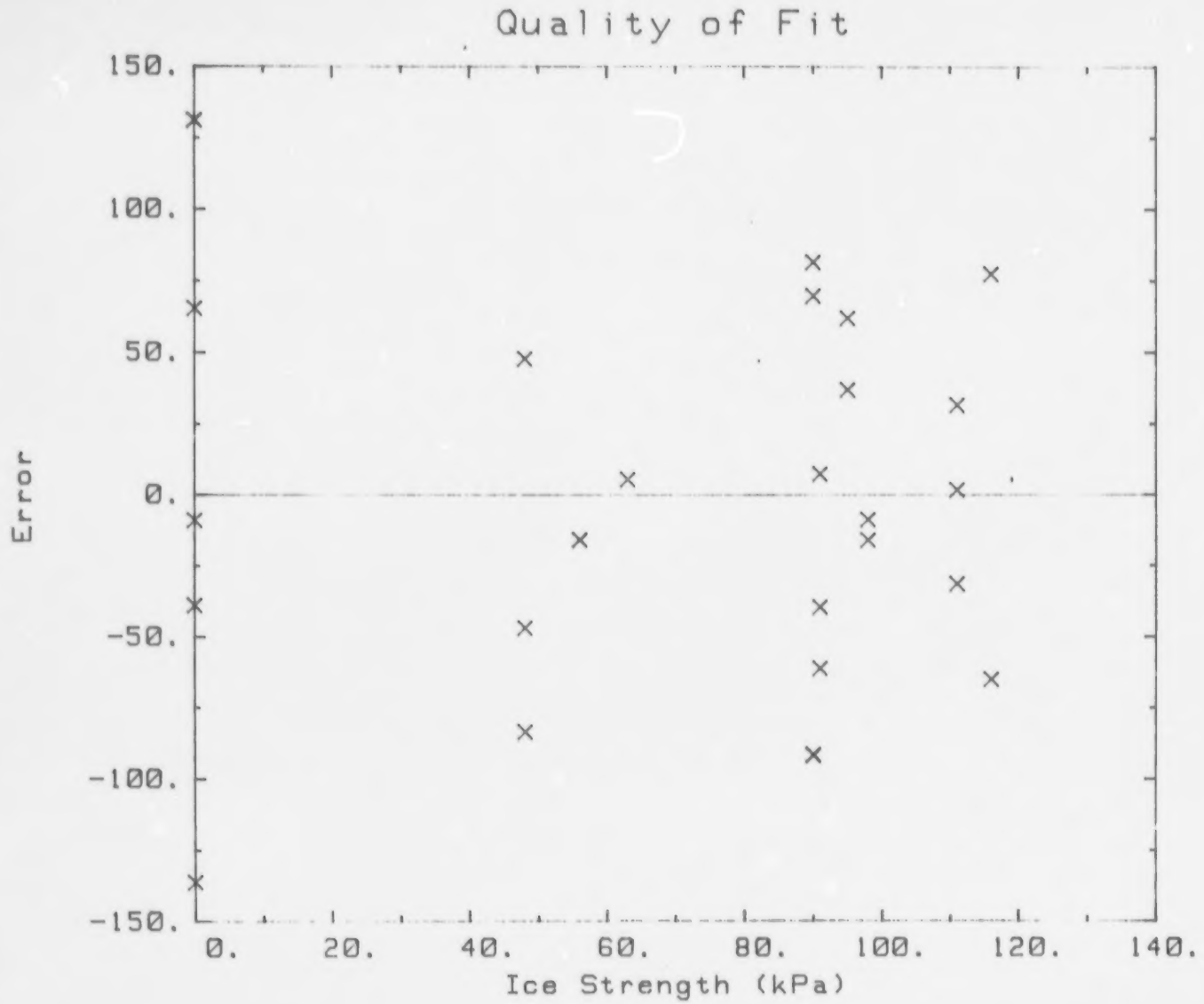
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100.
50.
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Error
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40.
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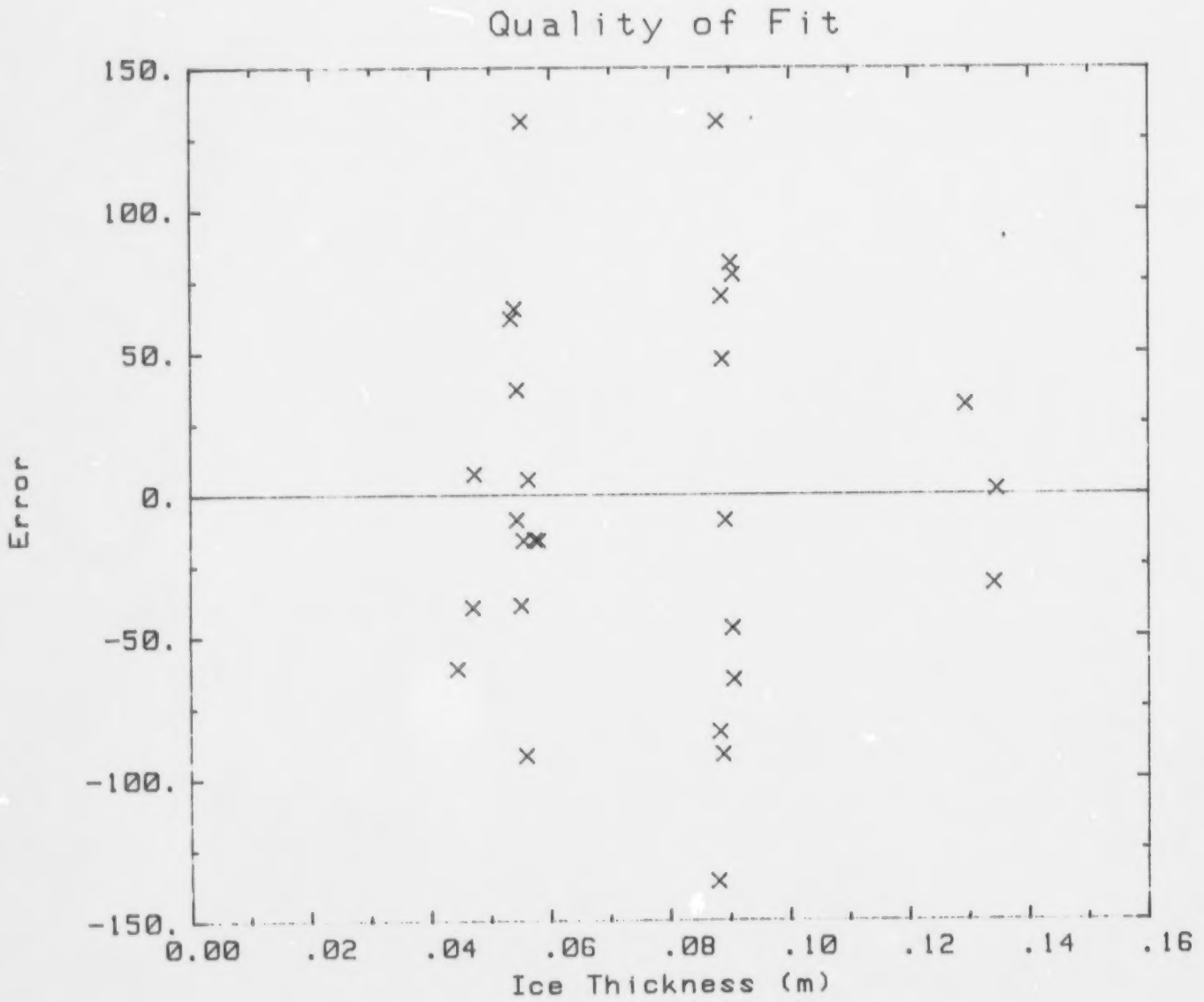
80.
100.
120.
140.
Ice Strength (kPa)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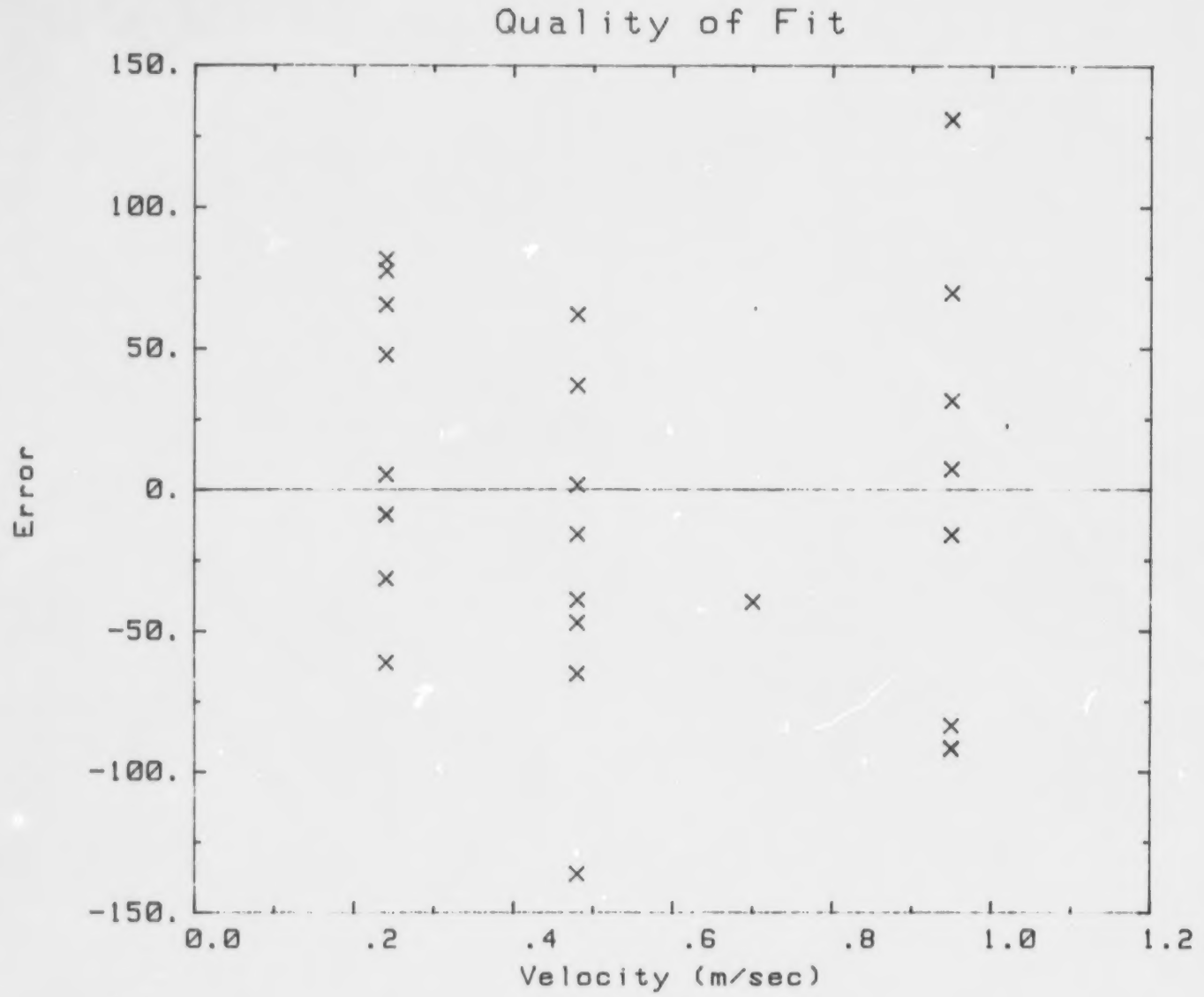
.16
Ice Thickness (m)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Error
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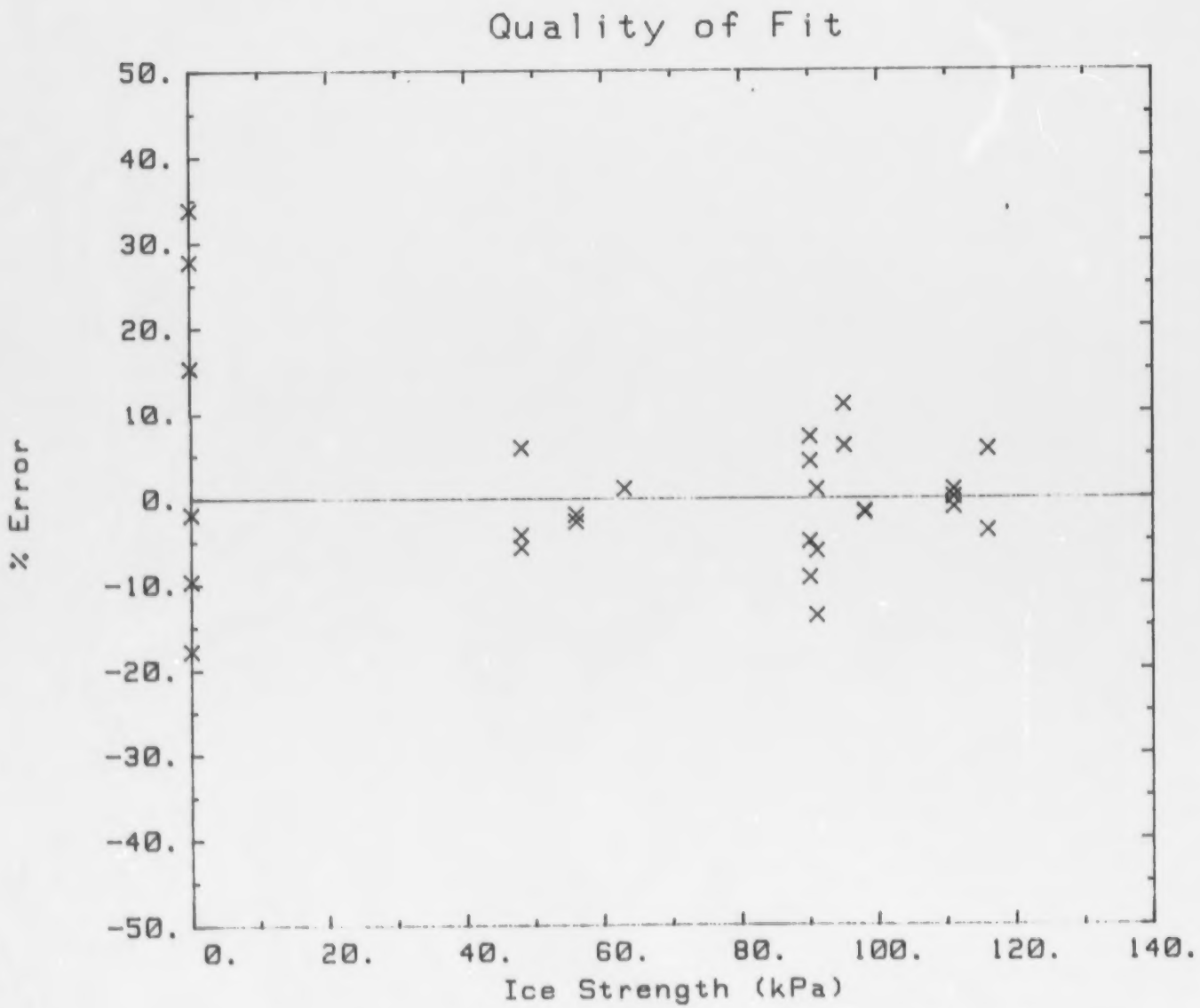
.4
.6
.8
1.0
1.2
Velocity (m/sec)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30.
20.
10.
0.
-10.
-20.
-30.
-40.
-50.
% Error
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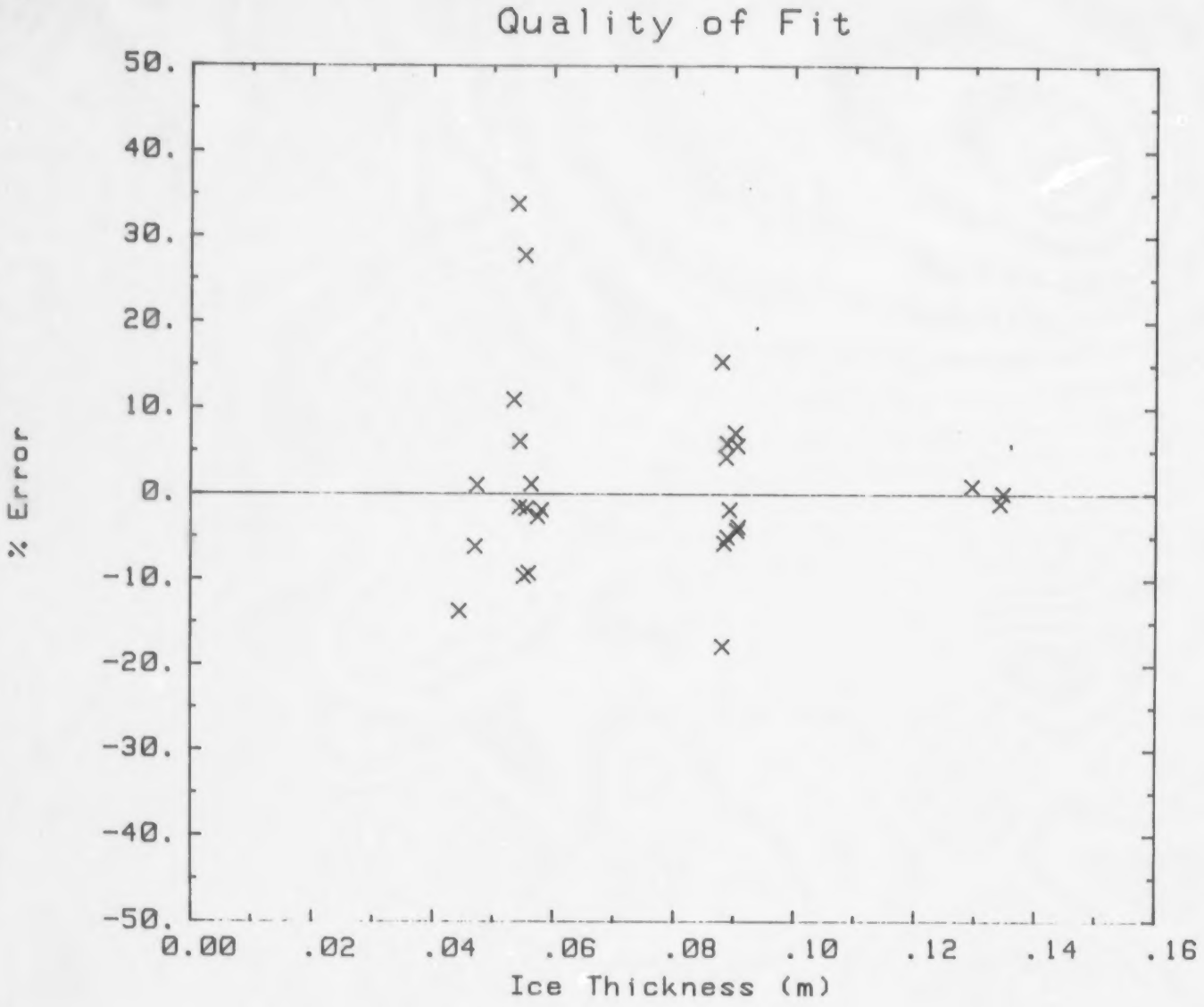
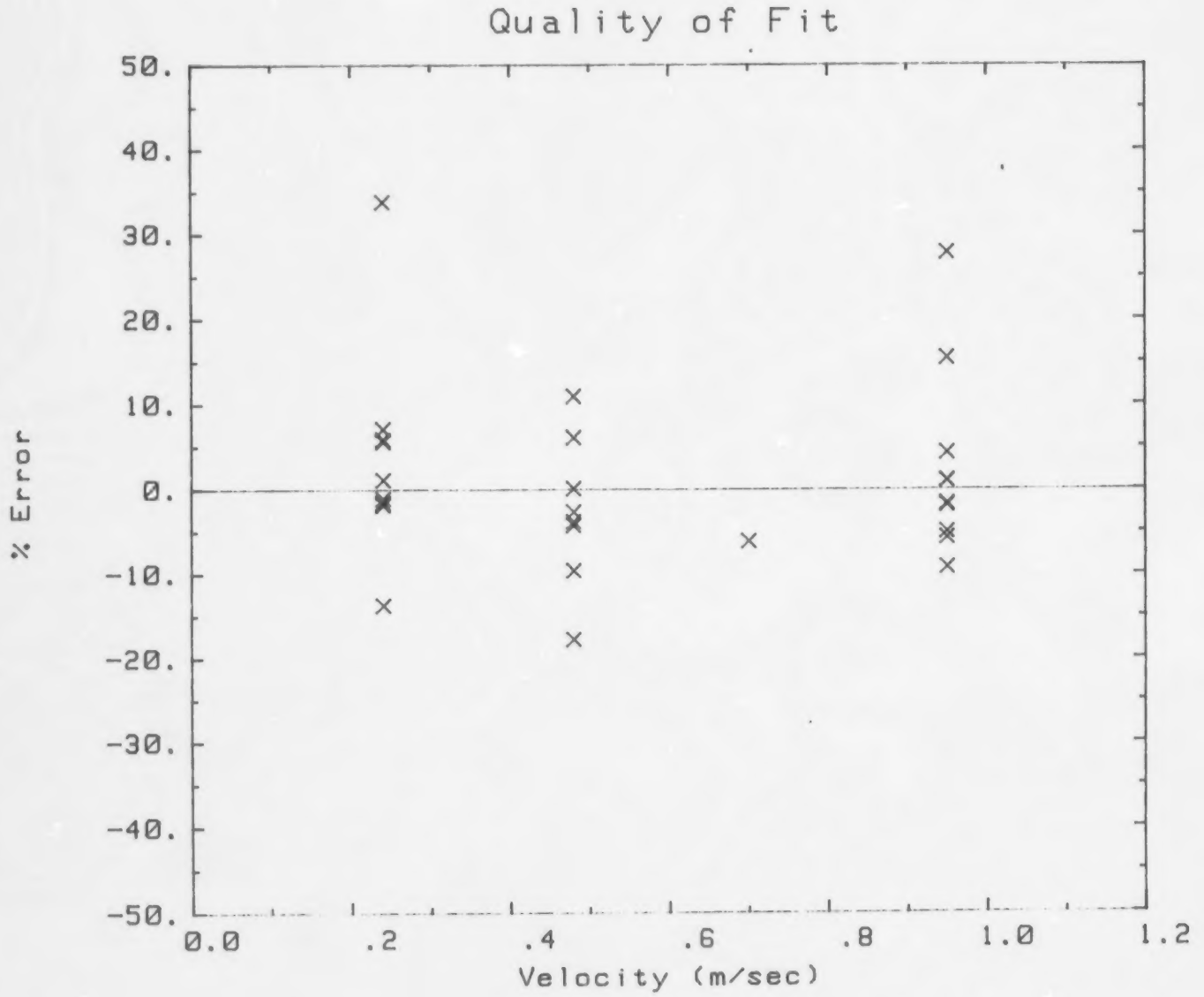
20.
40.
60.
80.
100.
120.
140.
Ice Strength (kPa)


Quality of Fit
50.
40.
30.
20.
10.
0.
-10.
-20.
-30.
-40.
-50.
% Error
0.00
.02
.04
.06
.08
.10
.12
.14
.16
Ice Thickness (m)


Quality of Fit
50.
40.
30.
20.
10.
0.
-10.
-20.
-30.
-40.
-50.
% Error
0.0
.2
.4
.6
.8
1.0
1.2
Velocity (m/sec)

APPENDIX III

ICE PIECE DATA

ICE SHEET #2
TEST #2
AVERAGE ICE THICKNESS 54.4 mm
AVERAGE ICE STRENGTH 98 KPa

Ice Piece No.	Length (m)	Width (m)	Area (m^2)
1	0.317	0.165	0.0522
2	0.424	0.321	0.1364
3	0.147	0.061	0.0089
4	0.160	0.049	0.0079
5	0.229	0.115	0.0263
6	0.851	0.274	0.2335
7	0.289	0.289	0.0837
8	0.329	0.224	0.0738
9	0.532	0.091	0.0486
10	0.226	0.150	0.0339
11	0.396	0.349	0.1381
12	0.425	0.268	0.1139
13	0.555	0.396	0.2197
14	0.210	0.468	0.0981
15	0.951	0.346	0.3287
16	0.670	0.167	0.1121
17	0.493	0.181	0.0891
18	0.179	0.089	0.0160
19	0.584	0.172	0.1003
20	0.283	0.333	0.0941
21	0.246	0.148	0.0365
22	0.229	0.163	0.0373
23	0.893	0.399	0.3557
24	0.774	0.124	0.0958
25	0.426	0.274	0.1166
26	0.941	0.147	0.1384
27	0.132	0.088	0.0117
28	0.218	0.087	0.0190
29	0.576	0.158	0.0911
30	0.236	0.208	0.0490
31	0.254	0.161	0.0408
32	0.127	0.051	0.0065
33	0.100	0.050	0.0050
Average	0.406	0.199	0.0915
Std. Deviation	0.253	0.114	0.0863

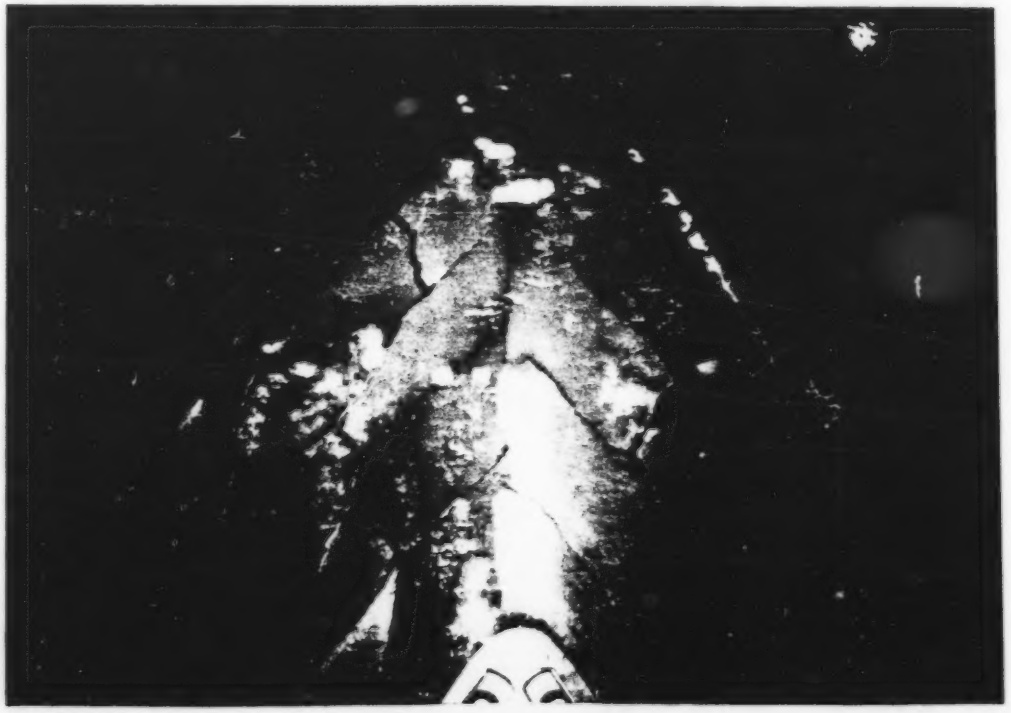
ICE SHEET #3
TEST #2
AVERAGE ICE THICKNESS 90.6 mm
AVERAGE ICE STRENGTH 116 KPa

Ice Piece No.	Length (m)	Width (m)	Area (m^2)
1	0.108	0.072	0.0078
2	0.075	0.050	0.0038
3	0.096	0.072	0.0069
4	0.074	0.037	0.0027
5	0.757	0.341	0.2578
6	0.568	0.177	0.1008
7	0.662	0.253	0.1676
8	0.659	0.142	0.0937
9	0.878	0.333	0.2923
10	0.869	0.227	0.1977
11	0.175	0.094	0.0164
12	0.532	0.259	0.1379
13	0.118	0.074	0.0087
14	0.951	0.219	0.2086
15	1.795	0.243	0.4369
16	0.630	0.280	0.1767
17	0.529	0.227	0.1201
18	0.454	0.182	0.0824
19	0.478	0.143	0.0686
20	0.670	0.196	0.1312
21	1.536	0.205	0.3145
22	1.621	0.205	0.3319
23	0.259	0.277	0.0718
24	0.555	0.259	0.1435
25	0.263	0.088	0.0230
26	0.071	0.071	0.0050
27	0.245	0.210	0.0515
28	1.594	0.246	0.3929
29	0.464	0.172	0.0796
30	1.526	0.325	0.4953
31	0.408	0.163	0.0667
32	0.217	0.124	0.0268
33	0.074	0.074	0.0055
34	0.446	0.201	0.0899
35	1.297	0.372	0.4828
36	0.260	0.275	0.0716
37	0.231	0.068	0.0157
38	1.312	0.182	0.2384
39	0.992	0.235	0.2329
40	0.258	0.168	0.0434
41	0.087	0.037	0.0032
42	0.491	0.245	0.1204
43	0.462	0.231	0.1067
44	0.064	0.051	0.0032
45	0.101	0.063	0.0064
46	0.086	0.037	0.0032
47	0.097	0.073	0.0070
48	0.095	0.024	0.0023
49	0.100	0.025	0.0025
Average	0.536	0.170	0.1216
Std. Deviation	0.486	0.095	0.1352

ICE SHEET #4
TEST #1
AVERAGE ICE THICKNESS 88.6 mm
AVERAGE ICE STRENGTH 90 KPa

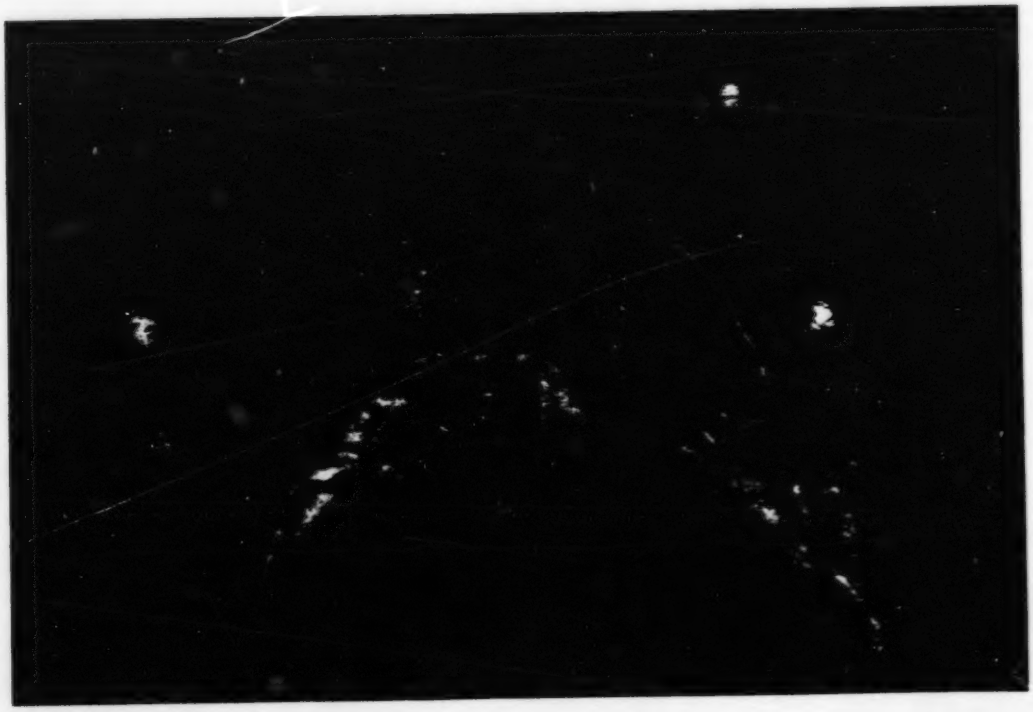
Ice Piece No.	Length (m)	Width (m)	Area (m^2)
1	0.107	0.048	0.0051
2	0.122	0.049	0.0060
3	0.775	0.181	0.1403
4	0.386	0.193	0.0746
5	0.780	0.161	0.1258
6	0.551	0.138	0.0758
7	0.317	0.051	0.0161
8	2.011	0.312	0.6263
9	1.381	0.285	0.3931
10	0.416	0.316	0.1315
11	0.813	0.159	0.1296
12	0.231	0.154	0.0355
13	1.323	0.161	0.2134
14	1.132	0.321	0.3637
15	0.529	0.166	0.0881
16	0.955	0.188	0.1796
17	1.029	0.206	0.2118
18	0.814	0.386	0.3143
19	0.431	0.210	0.0904
20	0.532	0.152	0.0810
21	0.117	0.078	0.0092
22	0.426	0.200	0.0850
23	0.308	0.099	0.0304
24	0.255	0.162	0.0413
Average	0.656	0.182	0.1445
Std. Deviation	0.469	0.090	0.1496

ICE SHEET #5
TEST #2
AVERAGE ICE THICKNESS 88.3 mm
AVERAGE ICE STRENGTH 48 KPa



Ice Piece No.	Length (m)	Width (m)	Area (m^2)
1	0.464	0.366	0.1700
2	0.608	0.158	0.0960
3	0.712	0.356	0.2532
4	0.480	0.260	0.1248
5	1.269	0.359	0.4551
6	0.725	0.378	0.2739
7	1.050	0.230	0.2418
8	1.845	0.681	1.2559
9	0.111	0.069	0.0077
10	0.830	0.386	0.3208
11	0.207	0.069	0.0143
12	1.413	0.278	0.3922
13	0.556	0.297	0.1651
14	0.289	0.251	0.0725
15	0.411	0.206	0.0846
16	0.387	0.176	0.0681
17	2.461	0.288	0.7081
Average	0.813	0.283	0.2767
Std. Deviation	0.625	0.143	0.3099

ICE SHEET #6
TEST #2
AVERAGE ICE THICKNESS 57.4 mm
AVERAGE ICE STRENGTH 56 KPa



Ice Piece No.	Length (m)	Width (m)	Area (m^2)
1	0.297	0.203	0.0603
2	0.360	0.180	0.0650
3	0.208	0.139	0.0288
4	0.787	0.106	0.0833
5	0.817	0.197	0.1606
6	0.464	0.224	0.1040
7	0.471	0.309	0.1454
8	1.000	0.539	0.5386
9	0.200	0.108	0.0215
10	0.629	0.161	0.1015
11	0.599	0.166	0.0997
12	0.412	0.190	0.0783
13	0.435	0.151	0.0656
14	0.768	0.239	0.1834
15	0.622	0.104	0.0645
16	0.453	0.109	0.0492
17	1.038	0.132	0.1372
18	0.577	0.112	0.0645
19	0.529	0.212	0.1119
20	0.286	0.135	0.0386
21	0.278	0.104	0.0291
22	0.977	0.172	0.1683
23	0.600	0.150	0.0900
24	0.808	0.197	0.1594
25	0.500	0.140	0.0701
26	1.083	0.444	0.4803
27	1.061	0.198	0.2100
28	1.256	0.187	0.2355
29	0.605	0.101	0.0610
30	1.108	0.155	0.1722
31	0.887	0.184	0.1634
32	0.751	0.163	0.1227
33	0.690	0.160	0.1106
34	0.527	0.161	0.0847
Average	0.650	0.183	0.1282
Std. Deviation	0.282	0.091	0.1108